THE WEBER RIVER BASIN AQUIFER STORAGE AND RECOVERY PROJECT

by

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ABSTRACT

The Delta aquifer, one of two confined aquifers in the east shore of Great Salt Lake aquifer system, is the primary source of ground water in the Ogden area. Long-term ground-water levels in the Ogden area have declined, probably related to increased withdrawals from wells for municipal and industrial use. From 1953 to 1985, water levels in the area declined an average of 27 feet (8 m), with a maximum drop of 50 feet (15 m) in areas of concentrated pumping; this trend in declining water level continues as a result if the current drought. This overdraft of the aquifer has not only increased pumping lifts and hence operational costs, but could also initiate land subsidence or salt-water intrusion from Great Salt Lake.

Aquifer storage and recovery within the Delta aquifer, either via land-surface infiltration or injection wells, potentially offers a partial solution to the problems associated with the water-level declines in the Ogden area. Not only would such an artificial ground-water recharge project stabilize the decline, but it would give water planners and managers increased flexibility in managing the water supply of the basin and provide them with a source of supplemental supply. During the 1950s, the U.S. Bureau of Reclamation conducted a series of on-site aquifer recharge experiments in the gravel pits at the mouth of Weber Canyon that resulted in water-level rises in observation wells; these experiments provided a preliminary indication of the feasibility of artificial ground-water recharge in this area.

The purpose of the study described in this report is to initiate further investigation of the potential and feasibility of aquifer storage and recovery in the Delta aquifer, and to provide a framework for a pilot project at the mouth of Weber Canyon. This four-phase project consists of: (1) a literature search and determination of data collection needs, (2) collection and analysis of baseline pre-project implementation data, (3) design and implementation of a pilot project, most likely at the mouth of Weber Canyon, and (4) collection of post-project data and evaluation of results to evaluate whether project goals were met. This report describes the hydrogeology of the project area, based on the literature search, and provides a summary of the results of phase 1, determination of data collection needs.

INTRODUCTION

The Weber River Basin Aquifer Storage and Recovery (WRBASR) project study area is located at the mouth of Weber Canyon, Weber and Davis Counties, in northern Utah (figure 1; plate 1). The Weber Delta area of the east shore aquifer system (Clark and others, 1990), containing the principal aquifer in Davis County and western Weber County, is referred to as the Weber Delta subdistrict of the Weber Delta district (figure 1) (Feth and others, 1966; Gates, 1995). The Weber Delta district covers an area of about 400 square miles (1,000 km^2), and extends westward from the Wasatch Range to the Great Salt Lake and southward from North Ogden to Farmington (figure 1) (Feth and others, 1966; Clark and others, 1990; Gates, 1995). The Weber River, which flows from east to west through the study area, is a primary source of recharge to aquifers in the Weber Delta district (Clark and others, 1990), and generally forms the boundary between Weber and Davis Counties. Two principal aquifers, the Sunset and Delta,

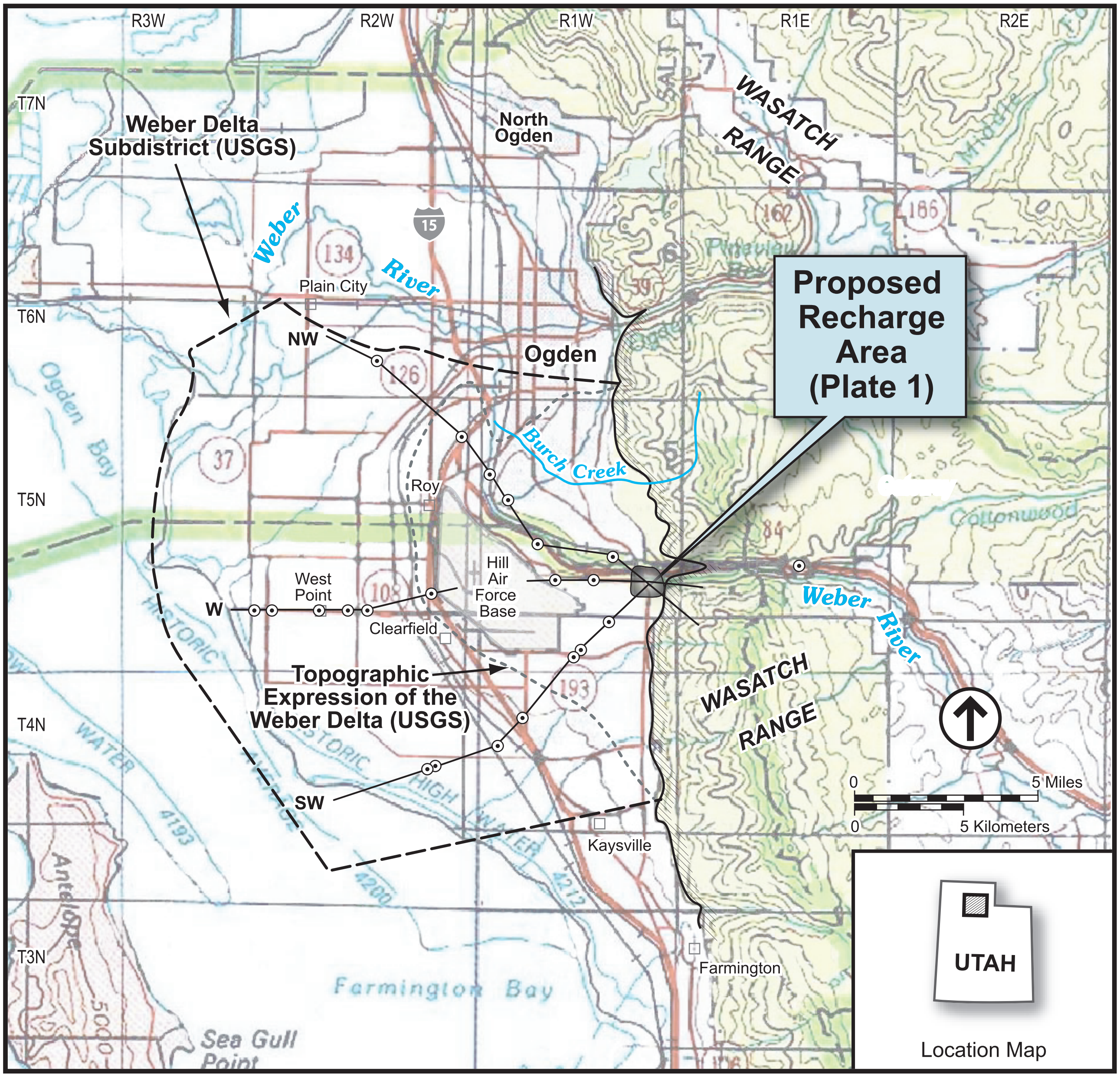


Figure 1. Locations of the Weber River Basin Aquifer Storage and Recovery project study area, Weber Delta, and the Weber Delta subdistrict (modified from Clyde and others, 1984).

have been delineated in the central part of the Weber Delta district (Feth and others, 1966) where ground water is generally under confined conditions; these two aquifers cannot be delineated along the western margin of the Wasatch Range where ground water is under unconfined conditions (Clark and others, 1990).

The Delta aquifer is the primary source of ground water in the Ogden area (Clark and others, 1990). Long-term ground-water levels in the Weber Delta district have declined, probably related to increased withdrawals from wells for municipal and industrial use (figure 2a; Clark and others, 1990). From 1953 to 1985, water levels declined an average of 27 feet (8 m) in wells located in the confined part of the Weber Delta district, with a maximum drop of 50 feet (15 m) near the principal pumping center for the district (Clark and others, 1990). From 1953 to 1985, water levels in the unconfined part of the Weber Delta district declined as much as 40 feet (12 m) in wells at the mouth of Weber Canyon (Clark and others, 1990), indicating that ground-water mining is a concern. The trend in declining water levels does not appear to have slowed; Burden and others (2000) documented water-level declines of up to 30.8 feet (9.4 m) from 1970 to 2000 (figure 2b). This overdraft of the aquifer has not only increased pumping lifts and hence operational costs, but could also initiate land subsidence or salt water intrusion from the Great Salt Lake.

Aquifer storage and recovery (ASR) within the Delta aquifer, either via land-surface infiltration or injection wells, potentially offers a partial solution to the problems associated with the water-level decline in the WRBASR project study area. Not only would such a project stabilize the decline, but it would provide water planners and managers with increased flexibility in managing the water supply of the basin and a source of supplemental supply. During the 1950s, the U.S. Bureau of Reclamation conducted a series of on-site aquifer recharge experiments in the gravel pits at the mouth of Weber Canyon (Clyde and others, 1984). Each of the experiments resulted in increased water levels in observation wells (Feth and others, 1966), and the experiments were deemed successful (Clyde and others, 1984).

Purpose and Scope

Artificial ground-water recharge has long been recognized as a means of introducing water into the ground-water system to enhance ground-water quality, reduce pumping lifts, store water, or salvage storm-water runoff (Clyde and others, 1984; Pyne, 1995). Basically, ground-water aquifers are used as water-storage facilities instead of constructing surface-water reservoirs. Aquifer storage and recovery projects involve the storage of water in an aquifer via artificial ground-water recharge when water is available, and recovery of the stored water from the aquifer during times when water is needed (Pyne, 1995). Artificial ground-water recharge can be accomplished by surface spreading or ponding of water in areas where surficial deposits are highly permeable, or by injection of surface water into an aquifer using wells (Clyde and others, 1984). Although losses of water stored via artificial ground-water recharge do occur, principally due to water moving vertically or laterally out of the target aquifer before recovery, the sometimes significant losses of water through evaporation in surface-water storage facilities are avoided (Clyde and others, 1984).

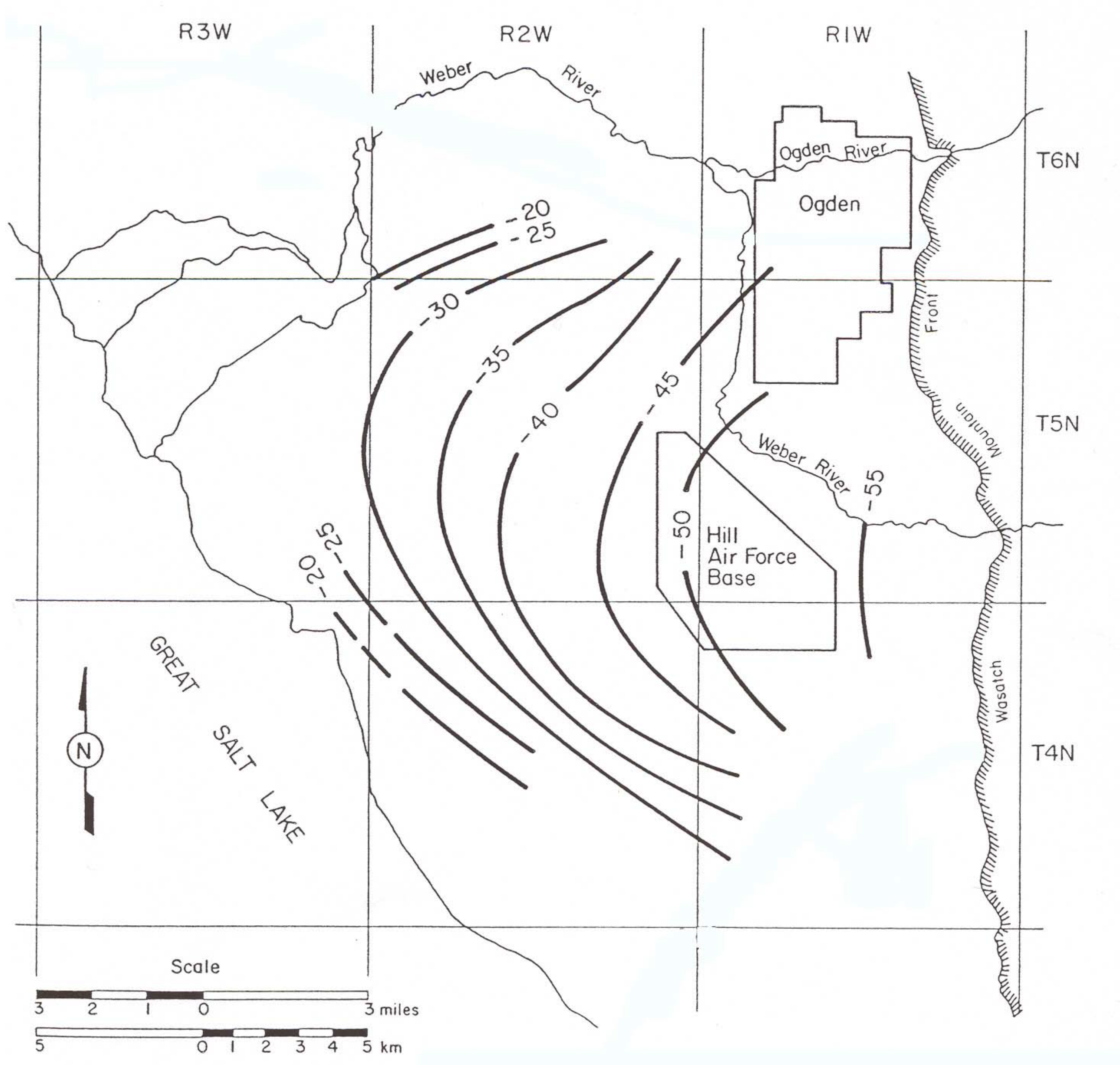


Figure 2a. *Change in piezometric surface for the Delta aquifer between 1937 and 1980, from Clyde and others (1984). Contours are lines of equal change in feet.*

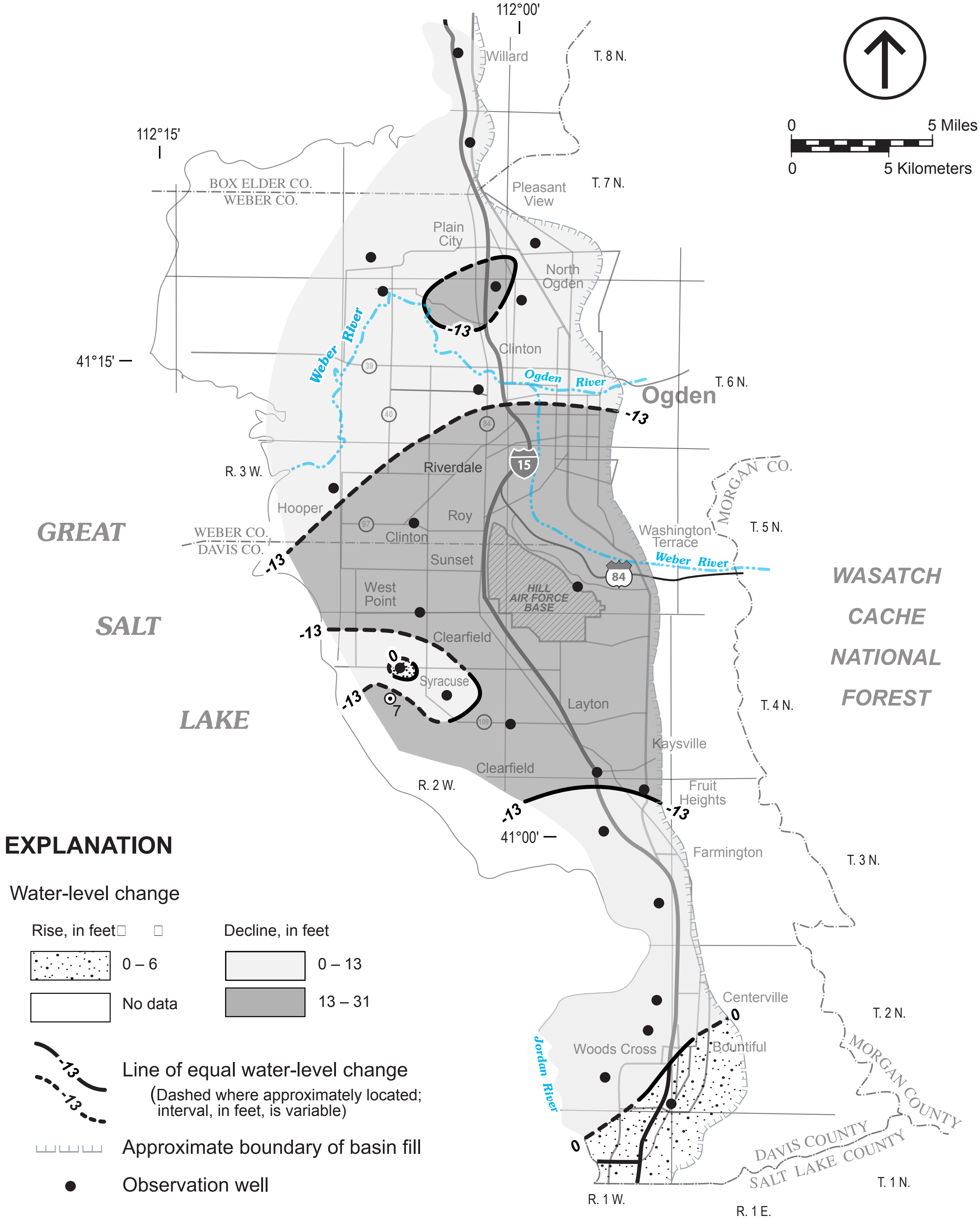


***Figure 2b.** Map of East Shore area showing change of water level from March 1970 to March 2000 (modified from Burden and others, 2000).*

The purpose of this study is to initiate further investigation of the potential and feasibility of aquifer storage and recovery in the Delta aquifer, and to provide a framework for a pilot project at the mouth of Weber Canyon. This project will take place over the next several years and build on knowledge obtained by previous investigators. We anticipate that this project will not only provide a means of stabilizing water levels in wells completed in the Delta aquifer, but that it will also provide water planners and managers with increased flexibility in managing and perhaps increasing ground-water resources. This project will also provide valuable data and insight into the practical application of aquifer storage and recovery in Utah and encourage the investigation of other similar projects in the state.

This is a phased-approach project conducted by personnel from the U.S. Bureau of Reclamation, Weber Basin Water Conservancy District, Utah Division of Water Resources, Weber State University Department of Geosciences, and Utah Geological Survey. Funding is provided by the U.S. Bureau of Reclamation. The project consists of four phases: (1) a literature search, primarily limited to the geology of the study area and previous artificial recharge experiments in Utah, and determination of data collection needs, (2) collection and analysis of baseline pre-project implementation data, (3) design and implementation of a pilot project, most likely at the mouth of Weber Canyon, and (4) collection of post-project data and evaluation of project results to evaluate whether project goals were met. This report describes the hydrogeology of the project area, based on the literature search, and provides a summary of the results of phase 1, determination of data collection needs. Surface spreading/ponding of water of the Weber River during spring runoff is presently considered the likely method to be utilized in the project, but injection of water via a well(s) may become the preferred alternative depending on the costs of leasing or purchasing property at the project location.

Location and Geography

The east shore area is a basin lowland extending northward from the Salt Lake salient to the town of Willard, Box Elder County, and from the western margin of the Wasatch Range to the eastern shore of Great Salt Lake (Clark and others, 1990). The project study area includes the central-eastern portion of the east shore area, and is in the lower Weber River drainage basin in northern Utah's heavily populated Wasatch Front (figure 1). The eastern part of the 10-square-mile (26 km^2) study area is in the Wasatch Range section of the Rocky Mountain physiographic province, and the western part of the project area is in the Ogden Valley segment of the Wasatch Front Valleys section of the Great Basin physiographic province (Stokes, 1977). Elevation ranges from about 5,800 feet (1,770 m) in the Wasatch Range in the southeast corner of the study area to about 4,420 feet (1,350 m) at the Weber River near the northwest corner of the study area (plate 1). The north-south-trending Wasatch fault zone near the base of the Wasatch Range is the approximate boundary between the two physiographic provinces.

The Weber Delta, the largest of the deltas associated with Pleistocene Lake Bonneville (Gilbert, 1890), was deposited mainly by the Weber and Ogden Rivers. Weber Delta deposits include interlayered, unconsolidated gravel, sand, and fine-grained deposits that are up to about 1,500 feet (457 m) thick near the canyon mouths and gradually thin to the west, north, and south (Feth and others, 1966; Clyde and others, 1984). Erosion of the Weber River through the Weber Delta has formed a terraced, flat-bottom, U-shaped trough through the center of the study area, with the arms of the U forming approximately 300-foot- (90 m) high bluffs extending to the top of the delta surface which is roughly at an elevation of 4,800 feet (1,460 m).

Population and Land Use

The study area (plate 1) is located a few miles south of Ogden, the county seat of Weber County. The communities of Uintah and Washington Terrace are located within the Weber County portion of the study area. The community of South Weber is located within the Davis County portion of the study area. The 2000 census populations of Ogden, South Weber, Uintah, and Washington Terrace were 77,226, 4,260, 1,127, and 8,551, respectively (Demographic and Economic Analysis Section, 2001); by 2030 the populations of these communities are expected to grow to 90,055, 13,768, 2,341, and 13,399, respectively (Demographic and Economic Analysis Section, 2000).

In addition to residential development, the principal land uses are U.S. Defense Department activities at Hill Air Force Base in the southwestern corner of the study area, commercial sales and rental businesses immediately northeast of Uintah Junction, job training at the Weber Basin Job Corp Center in the eastern part of the study area, and the mining of gravel, also in the eastern part of the study area. The Weber River is used for recreational activities such as fishing.

Climate

The study area has a temperate and semi-arid climate (Feth and others, 1966). Based on data from a weather station in Riverdale, temperatures in the study area reach a normal maximum of 90.5 ^{o}F (32.5 ^{o}C) in July and a normal minimum of 18.1 ^{o}F (-7.7 ^{o}C) in January; the normal mean annual temperature is 46.6 ^{o}F (8.1 ^{o}C) (Ashcroft and others, 1992). Normal mean annual precipitation is 19.49 inches (49.5 cm); normal mean annual evapotranspiration is 45.29 inches (115.0 cm) (Ashcroft and others, 1992). The average number of frost-free days is 151 (Ashcroft and others, 1992).

PREVIOUS INVESTIGATIONS

An early study of ground-water conditions in the Weber Delta district was conducted by Dennis and McDonald (1944). Dennis (1952) evaluated ground-water recharge in the east shore area. Feth and others (1966) conducted a comprehensive study of basin-fill deposits and hydrogeologic conditions in the Weber Delta district; they also reported on U.S. Bureau of Reclamation artificial recharge experiments at the mouth of Weber Canyon during the 1950s (Feth and others, 1966). Smith (1961) provided basic data on water levels and ground-water quality for the east shore area, and Smith and Gates (1963) evaluated changes in ground-water quality and water levels based on that data for the 1953 to 1961 time period. Bolke and Waddell (1972) mapped ground-water quality and evaluated changes in water levels and ground-water quality in the east shore area for the 1960 to 1969 time period. Clyde and others (1984) constructed a ground-water model which they used to evaluate the potential for diverting water from the Weber River at the mouth of Weber Canyon for use as a source of artificial recharge for the Weber Delta area. Clark and others (1990) re-evaluated ground-water conditions in the east shore area and constructed a digital-computer model of the east shore aquifer in the Weber Delta area to evaluate the effects of ground-water withdrawals. Anderson and others (1994; see also Anderson and Susong, 1995) mapped ground-water recharge and discharge areas for the principal aquifers along the Wasatch Front, including aquifers in the Weber Delta district. Gates (1995) provided a description and quantification of ground-water basins along the Wasatch Front, including a discussion of how water budgets changed from one ground-water study to the next. Burden and others (2000) described changes in ground-water conditions in Utah, including the east shore area from 1970 to 2000. Yonkee and Lowe (in preparation) summarized ground-water conditions in the Ogden 7.5-minute geologic quadrangle based on the ground-water reports discussed above; this summary provides the basis for the discussion of ground-water conditions presented herein.

Geologic maps covering the study area include: a regional map of the Farmington Canyon Complex by Bryant (1984, scale 1:100,000); a regional map of the northern Wasatch Front compiled by Davis (1985, scale 1:100,000); a map of surficial deposits along the Wasatch fault zone by Nelson and Personius (1993, scale 1:50,000); and soil-survey maps of the Davis-Weber area (Erickson and others, 1968, scale 1:15,840). A 1:24,000-scale geologic map of the Ogden 7.5-minute quadrangle by Yonkee and Lowe (in preparation) is the principal source of geologic mapping used for this study.

GEOLOGIC AND HYDROLOGIC SETTING

Geologic units exposed in the study area include a variety of surficial deposits and the Precambrian Farmington Canyon Complex (figure 3). Quaternary deltaic, fluvial, alluvial-fan, and landslide deposits overly a thick sequence of Quaternary-Tertiary basin-fill deposits in the western part of the study area. The Farmington Canyon Complex, which forms the Wasatch Range in the study area, consists of Early Proterozoic high-grade metamorphic and igneous rocks (Bryant, 1984). The principal structural feature in the study area is the Wasatch normal-fault zone, which formed during late Cenozoic extensional deformation (Hintze, 1988). Many of the fractures in bedrock of the Wasatch Range formed during Cretaceous contractional deformation (Yonkee and Lowe, in preparation).

Stratigraphy

Quaternary Surficial Deposits

Quaternary surficial deposits were formed by lacustrine, deltaic, alluvial, mass-wasting, and glacial processes (figure 3; appendix A). These deposits generally form a thin veneer over Quaternary and Tertiary basin-fill deposits. Lacustrine deposits are mixed gravel and sand near the mountain front, grading westward to sand, silt, and clay. Deltaic, alluvial, and glacial

Explanation

Symbols

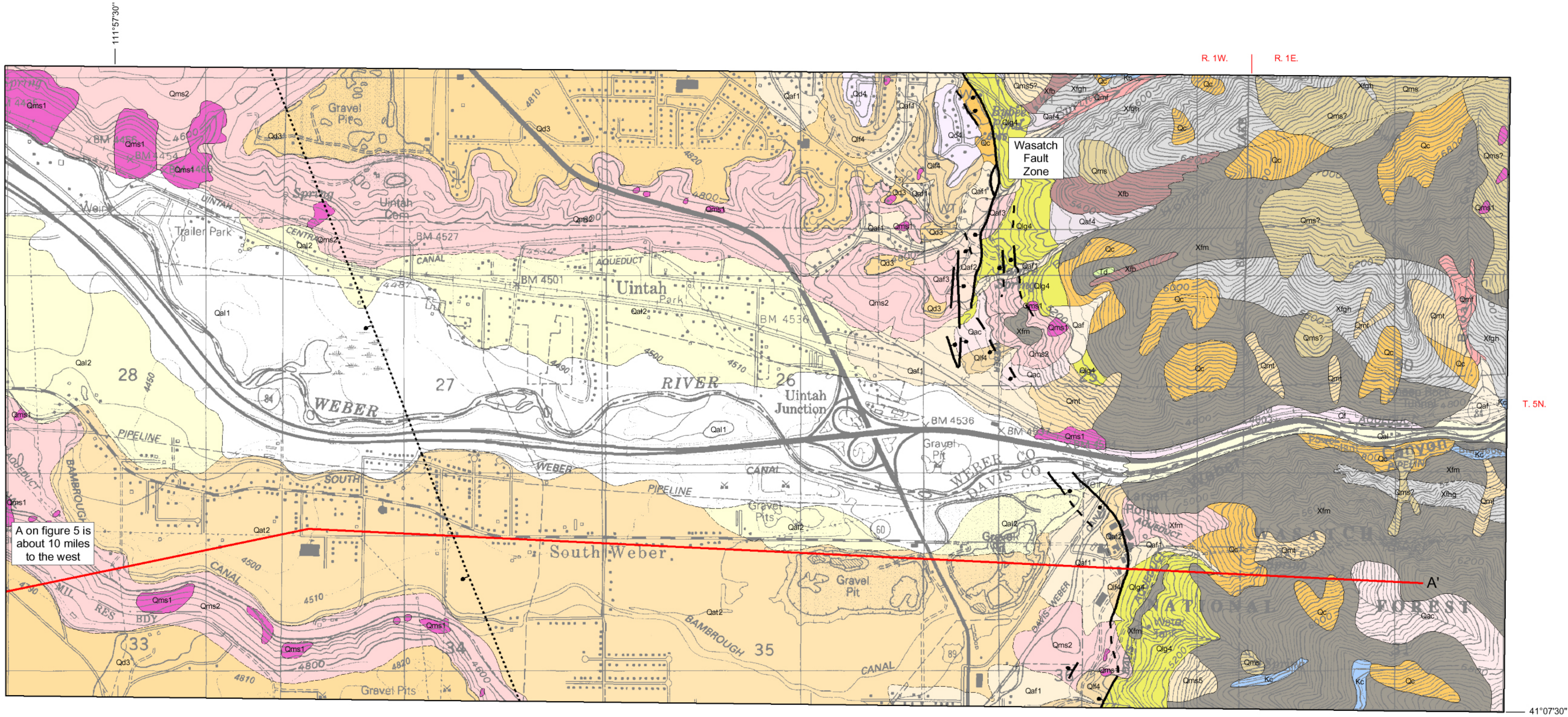
- Contact
- Contact located approximately
- Contact located very approximately

Normal fault

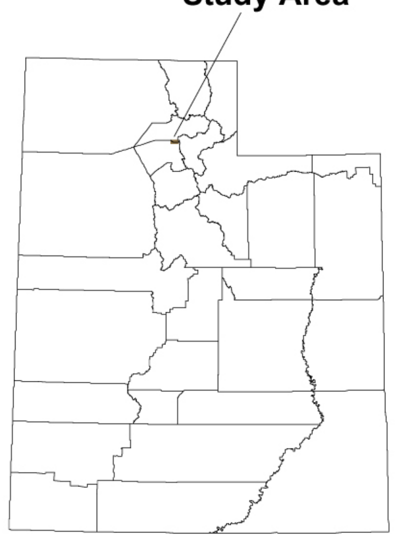
- Bar and ball on downthrown side
- Fault (Concealed)
- Fault (Inferred)
- ? Unit designation uncertain
- A—A' Cross section (figure 5)

Units - see appendix B for descriptions

- Qf - Artificial fill
- Qac - Colluvium and alluvium, undivided
- Qc - Colluvium
- Qmt - Talus
- Qmf - Debris-flow deposits
- Qms1 - Landslide deposits, younger Holocene
- Qms2 - Landslide deposits, middle and older Holocene
- Qms5 - Landslide deposits, pre-Bonneville to Bonneville-transgressive
- Qms - Landslide deposits, undivided
- Qaf1 - Alluvial-fan deposits, younger Holocene
- Qaf2 - Alluvial-fan deposits, middle and older Holocene
- Qaf3 - Alluvial-fan deposits, Bonneville-regressive
- Qaf4 - Alluvial-fan deposits, Bonneville-transgressive
- Qaf - Alluvial-fan deposits, undivided
- Qal1 - Stream alluvium, younger Holocene
- Qal2 - Stream alluvium, middle Holocene
- Qal - Stream alluvium, undivided
- Qat2 - Alluvial-terrace deposits, older Holocene
- Qd3 - Delta deposits, Bonneville-regressive
- Qd4 - Delta deposits, Bonneville-transgressive
- Qlf4 - Lacustrine fine-grained deposits, Bonneville transgressive
- Qlg4 - Lacustrine gravel-bearing deposits, Bonneville-transgressive
- Td - Tertiary igneous dikes
- Kc - Chloritic gneiss, cataclasite, and mylonite
- Xfgh - Granitic gneiss of Ogden hanging wall
- Xfm - Migmatitic gneiss
- Xfb - Biotite-rich schist



Study Area



1:24,000

0 0.25 0.5 1 Miles

0 0.25 0.5 1 Kilometers

Figure 3. Geologic map of the Weber River Aquifer Storage and Recovery Project Area, Weber County, Utah.

Geologic mapping from Yonkee and Lowe, in preparation.

Digital compilation by Matt Butler.

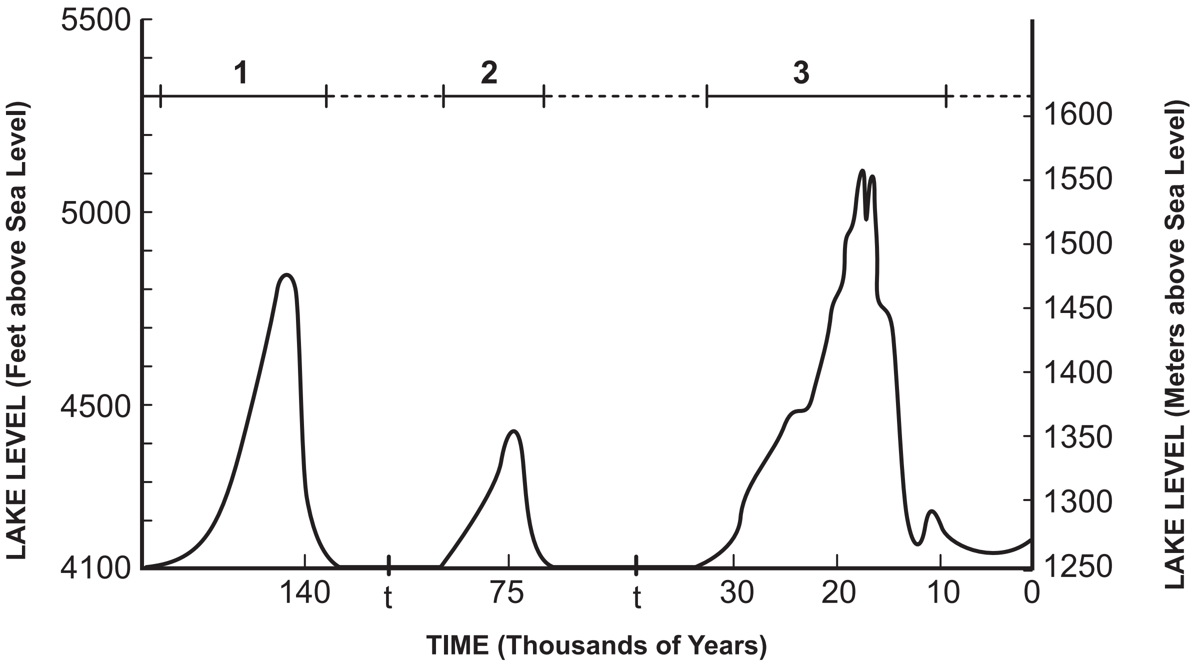
deposits are predominantly sand and gravel. Mass-wasting deposits contain chaotic mixtures of large bedrock blocks and detritus ranging from clay to boulder size.

Basin Fill

The Ogden Valley segment of the Wasatch Front Valleys section of the Basin and Range physiographic province is a north-south-trending structural graben that has been the site of accumulation of great thicknesses of sediment since its inception in early Tertiary time (Eardly, 1955). The active Wasatch normal fault forms the eastern margin of this depositional basin. Gravity, seismic, and drill-hole data indicate that the sediments filling this graben are locally up to 10,000 feet (3,000 m) thick in some areas (Feth and others, 1966; Cook and others, 1967; Glenn and others, 1980; Zoback, 1983; McNeil and Smith, 1992). The basin fill likely includes an older sequence of more tilted, Eocene to Oligocene strata consisting of a mixture of conglomerate, sandstone, reworked tuff, and minor lacustrine limestone similar to those preserved beneath parts of eastern Great Salt Lake (Constenius, 1996) and locally exposed on Antelope Island (Willis and Jensen, 2000). These older basin-fill deposits are overlain by Miocene to Pliocene rocks that are generally assigned to the Salt Lake Formation and which consist of heterogeneous mixtures of poorly consolidated sedimentary rocks and reworked tuff (Miller, 1991). This Miocene to Pliocene basin fill is, in turn, overlain by less consolidated Quaternary basin fill and surficial deposits of predominantly fluvial, lacustrine, and deltaic origin (Feth and others, 1966). The Quaternary basin-fill sediments are the primary focus of this report because they comprise the principal ground-water aquifers.

The study area is within the hydrologically closed Lake Bonneville basin, and water flowing into this basin generally leaves it only by evapotranspiration. The Lake Bonneville basin has been an area of internal drainage for much of the past 15 million years, and lakes of various sizes have existed in the area during most of that time (Currey and others, 1984). Figure 4 is a schematic diagram showing the approximate time periods of, and the approximate lake-surface elevations reached during, the last three lake cycles in the Lake Bonneville basin. Due to this history of deep-lake cycles interspersed with periods when lakes stood at low levels or were not present, the Quaternary basin-fill deposits consist of complexly interfingering, overall westward-fining bodies of gravel, sand, silt, and clay deposited in lacustrine and fluvial environments (Feth and others, 1966; Sprinkel, 1993).

The Quaternary lacustrine and fluvial basin-fill deposits can be divided into a lower interval, the Delta aquifer; a middle confining interval, the Sunset aquifer; and an upper confining interval (figure 5; Feth and others, 1966). The lower interval was partly deposited in a marginal lacustrine environment and consists mostly of thin-bedded silt and fine sand (Sprinkel, 1993). The Delta aquifer consists mostly of fluvial, interbedded cobble to pebble gravel and gravelly sand. The middle confining interval consists mostly of thin-bedded silt and fine sand, with some layers of pebbly sand, deposited in marginal lacustrine and fluvial environments (Sprinkel, 1993). The Sunset aquifer consists of pebble gravel, pebbly sand, and well-sorted medium to coarse sand of fluvial origin. The upper confining interval consists mostly of thin-bedded silt and sand likely deposited in a brackish lacustrine environment. The deposits forming each of these aquifers gradually thin and become increasingly finer grained away from the canyon mouths.



Explanation

1 - Little Valley lake cycle.

2 - Cutler Dam lake cycle.

3 - Bonneville lake cycle.

t - Splice point on graph. Periods of time during interlacustrine phases have been removed to condense graph.

Figure 4. *Schematic diagram showing a hydrograph of probable lake levels in the Lake Bonneville basin for the past 150,000 years. Numbered solid lines above lake level curves represent time periods of lake cycles described in this report. Dashed lines represent interlacustrine periods when lakes in the Lake Bonneville basin stood at relatively low levels or were nonexistent. (Hydrograph modified from Currey and Oviatt, 1985, and extended past 35,000 years before present on the basis of stratigraphic studies of pre-Lake Bonneville deposits by Machette and others, 1992, with additional modifications for this report).*

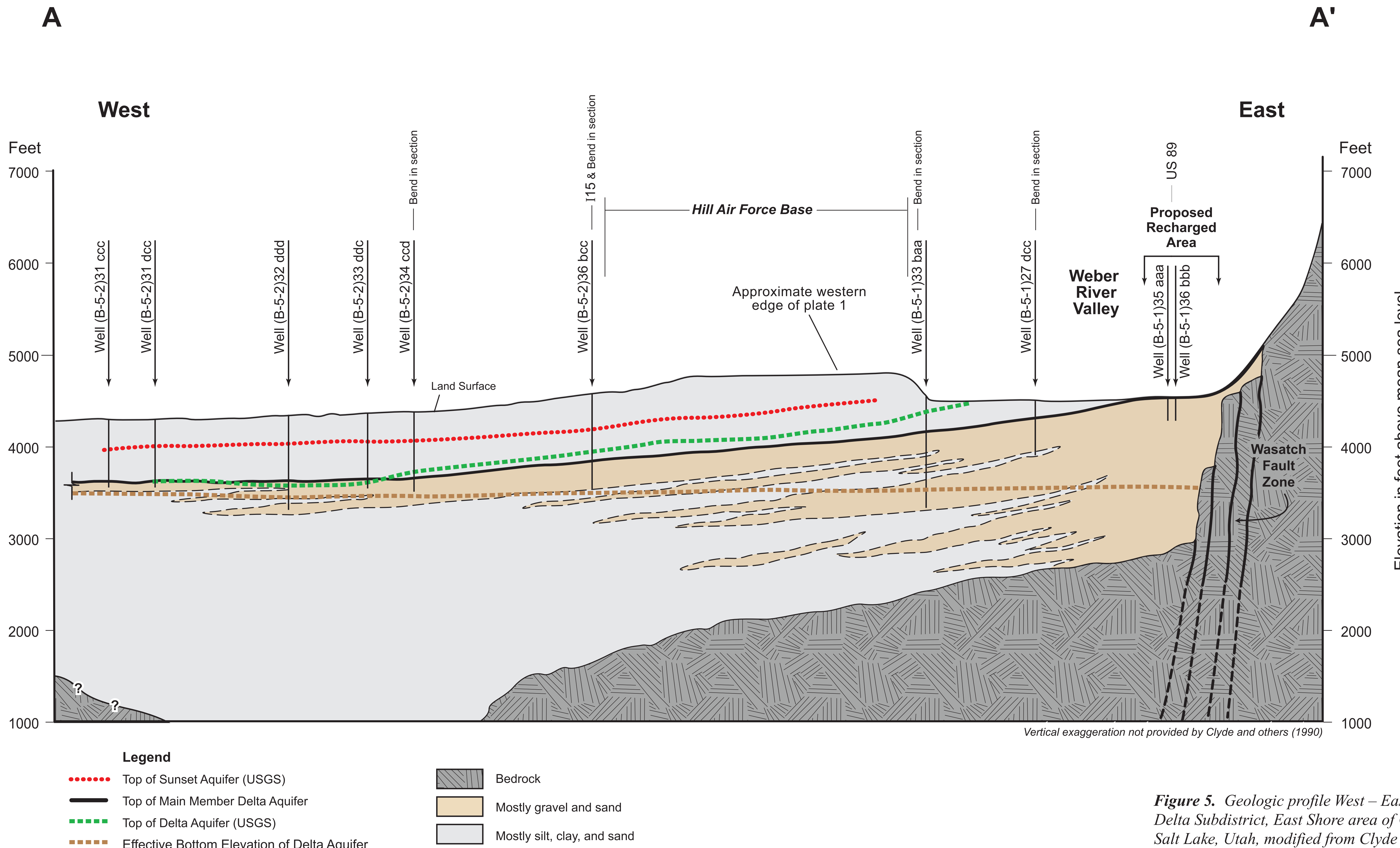


Figure 5. *Geologic profile West – East, Weber Delta Subdistrict, East Shore area of Great Salt Lake, Utah, modified from Clyde and others (1984). See appendix B for explanation of well-numbering system.*

Early Proterozoic Farmington Canyon Complex

A complex mixture of high-grade metamorphic and igneous rocks comprise the Farmington Canyon Complex, which is exposed in the Wasatch Range in the eastern part of the study area (figure 3) (Eardley, 1944; Bryant, 1984; Yonkee and others, 2000). The Farmington Canyon Complex includes meta-ultramafic and mafic rocks, quartz-rich gneiss, biotite-rich schist, migmatitic gneiss, and granitic gneiss (appendix A; Yonkee and Lowe, in review).

Water Resources

Surface Water

The Weber River contributes the vast majority of surface water flowing into and through the study area. Annual flow in the Weber River at a gaging station near Ogden averaged 0.32 cubic kilometers per year (260,000 acre-feet/year) from 1890 to 1993 (Utah Division of Water Resources, 1997, table 5-1). Flow along the Weber River increases in Weber Canyon due to bedrock recharge and decreases west of the mouth of Weber Canyon where the river loses water into basin fill (Feth and others, 1966). The likelihood of flooding from snowmelt runoff is highest from late April to early July (figure 6) (Federal Emergency Management Agency, 1982).

Chemical analyses of Weber River water from a site about 4 miles (6 km) east of the mouth of Weber Canyon (table 1) indicate the water did not exceed ground-water quality standards for any of the analyzed constituents for the 2000 to 2002 sampling periods.

Spring Creek Canyon to the north of the Weber River is an intermittent stream with permanently flowing stretches and stretches that are seasonally dry. Ephemeral streams, which are completely dry during much of the year, drain the smaller canyons along the mountain front and the sides of Weber Canyon.

Ground Water

Bedrock aquifers. Fractured parts of the Precambrian Farmington Canyon Complex likely form aquifers with highly variable permeability and low storage, based on comparison to the Park City, Utah area (Ashland and others, 2001; Yonkee and Lowe, in preparation). The Gateway tunnel, which penetrated the Farmington Canyon Complex in the Wasatch Range just south of Weber Canyon, encountered considerable fluid flow at various fractured intervals, with total discharge ranging from 180 to 450 gallons per minute (12-30 L/s) during completion of the tunnel in 1955 (Feth and others, 1966). Discharge increased markedly during April and May, reaching a peak in June, and then decreased during late summer to fall, consistent with recharge during snowmelt and limited storage (Yonkee and Lowe, in preparation). The Weber River gains in flow by about 2,000 gallons per minute (130 L/sec) over a stretch of about 0.5 miles (0.8 km) along lower Weber Canyon, probably related to inflow from the Farmington Canyon Complex

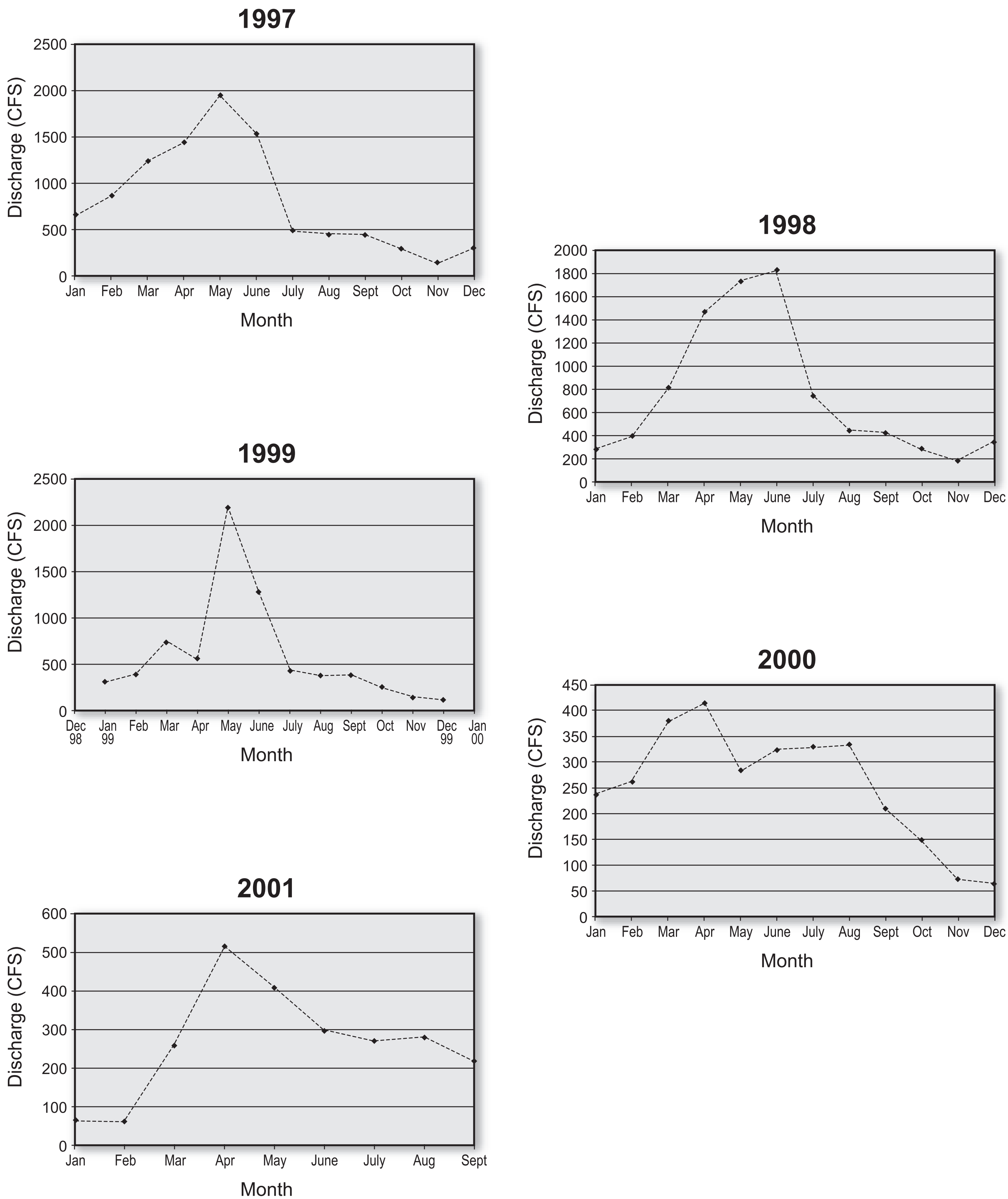


***Figure 6**. Monthly hydrographs from 1997 to 2001 of Weber River at Gateway near the head of Weber Canyon just east of the study area.*

Table 1. WATER-QUALITY DATA, WEBER RIVER - GATEWAY TO POWERHOUSE

*ND = Non-Detect — ug/L = micrograms per liter
- = No data — mg/L =milligrams per liter

Date Sampled	Time Sampled	Alkalinity, Carbonate as $CaCO_3$ mg/L	Aluminum ug/L	Arsenic ug/L	Barium ug/L	Bicarbonate mg/L	BOD, Biochemical oxygen demand	Cadmium ug/L	Calcium mg/L	Carbon dioxide mg/L	Carbonate ion (CO_{3-2}) mg/L	Chloride mg/L
1/5/2000	15:32:00	210	*ND	*ND	120	256	-	*ND	75.9	3	0	39.5
6/13/2000	13:35:00	184	-	-	-	224	-	-	61.5	1	0	32
1/31/2001	13:10:00	244	*ND	*ND	144	298	*ND	*ND	79.2	4	0	42
5/3/2001	14:55:00	81	181	*ND	55.3	99	*ND	*ND	26.7	2	0	*ND
1/22/2002	17:00:00	238	-	-	-	290	*ND	-	75	3	0	48.2
6/26/2002	10:15:00	202	-	-	-	246	-	-	71.1	2	0	31.5

Date Sampled	Chromium ug/L	Copper ug/L	Dissolved Solids mg/L	Hardness Ca + Mg mg/L	Hydroxide mg/L	Iron ug/L	Lead ug/L	Magnesium mg/L	Manganese ug/L	Mercury ug/L	Nitrogen, Nitrite (NO_2) + Nitrate (NO_3) as N mg/L	pH
1/5/2000	5	*ND	326	272.1	0	*ND	*ND	20.1	12	*ND	0.7	8.21
6/13/2000	-	-	266	219.7	0	-	-	16.1	-	-	0.3	8.47
1/31/2001	*ND	*ND	372	280.7	0	*ND	*ND	20.2	45.9	*ND	1.04	8.1
5/3/2001	*ND	*ND	134	92.7	0	78.1	*ND	6.33	17.9	*ND	0.32	7.93
1/22/2002	-	-	-	274.4	0	-	-	21.2	-	-	*ND	8.23
6/26/2002	-	-	314	251.5	0	-	-	18	-	-	0.3	8.4

Date Sampled	Phosphorus as P mg/L	Potassium mg/L	Selenium ug/L	Silver ug/L	Sodium mg/L	Specific conductivity umho/cm	Sulfate (SO_4) as SO_4 mg/L	Total Suspended Solids (TSS) mg/L	Turbidity NTU	Zinc ug/L
1/5/2000	*ND	2.66	*ND	*ND	24.9	580	28.3	0	2.29	*ND
6/13/2000	0.035	2.42	-	-	19.4	456	24.9	4	1.73	-
1/31/2001	0.024	2.74	*ND	*ND	24.6	646	36.9	0	1.45	*ND
5/3/2001	0.041	1.02	*ND	*ND	8.08	195	*ND	*ND	7.56	*ND
1/22/2002	0.042	3.1	-	-	29.3	636	34	*ND	1.53	-
6/26/2002	0.022	2.54	-	-	22.6	535	23.1	*ND	1.95	-

DATA SOURCE: Utah Division of Water Quality

(Feth and others, 1966). The overall direction of ground-water flow in the Farmington Canyon Complex is likely westward, from higher elevations near the mountain crest toward lower elevations along the mountain front on the west side of the Wasatch Range, with local flow toward canyon bottoms, especially along Weber Canyon. Some discharge from the Farmington Canyon Complex is to springs and gaining parts of streams along the mountain front, and additional discharge may occur to basin-fill aquifers via flow across the Wasatch fault zone at depth (Yonkee and Lowe, in preparation).

Basin-fill aquifers. The most important ground-water resources in the east shore area occur in unconsolidated to semi-consolidated Quaternary basin-fill deposits (Feth and others, 1966; Clark and others, 1990). These deposits consist of overall coarser grained alluvial sediments near the mountain front, and overall finer grained lacustrine and fluvial sediments westward away from the mountains (Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). Deeper ground water in the aquifer system is predominantly confined, but unconfined conditions exist locally in recharge areas, and form a narrow band along the Wasatch mountain front (Anderson and others, 1994); this area of unconfined conditions is widest at the mouth of Weber Canyon. Two principal aquifers, the Sunset and Delta, have been delineated in the central part of the Weber Delta district (figure 5) (Feth and others, 1966). The Delta aquifer is the primary source of ground water in the northern Davis County and southwestern Weber County area, and is composed mostly of coarse-grained, pre-Bonneville fluvial and deltaic sediments (Clark and others, 1990). The top of the Delta aquifer is 500 to 700 feet (150-200 m) below the ground surface in the eastern part of the Weber Delta subdistrict, and the aquifer is about 50 to 200 feet (15-60 m) thick (figure 5) (Feth and others, 1966). The shallower Sunset aquifer has a lower permeability and is used to a lesser extent as a source of ground water. The top of this aquifer is 200 to 400 feet (60-120 m) below the ground surface in the Weber Delta subdistrict, and it is about 50 to 200 feet (15-60 m) thick (figure 5) (Feth and others, 1966). Fine-grained confining intervals overlie both aquifers away from the mountain front. A shallow unconfined aquifer is commonly found above the upper confining beds within Quaternary surficial deposits (Clark and others, 1990). Tertiary basin fill deeper than about 1,500 feet (450 m) tends to be better lithified, less permeable, and contains poorer quality water, and thus is not considered an important ground-water source (Clark and others, 1990).

Faults. Major faults, such as the Wasatch fault zone, likely influence ground-water flow in both bedrock and basin fill, with fractured zones preferentially transmitting water parallel to the fault, and fine-grained gouge zones tending to inhibit flow across the fault (Caine and others, 1996). Several warm springs north of the study area near the mouth of Ogden Canyon are located near the Wasatch fault zone in fractured footwall rocks of the Farmington Canyon Complex, including Ogden Hot Spring. Ogden Hot Spring has a flow of about 520 to 1,500 gallons per minute (35-100 L/s) and a water temperature of about 135 °F (55 °C) (Mundorff, 1970). Water from the spring has 8,000 to 9,000 parts per million (ppm) total dissolved solids (TDS), and is of sodium-chloride type (Mundorff, 1970). Dissolved silica content of the spring water indicates interaction with rocks at temperatures of about 210 °F (100 °C) (Glenn and others, 1980), giving an estimated depth of circulation for waters discharged by the springs of about 10,000 feet (3,000 meters) for a geothermal gradient of 30 °C/kilometer (Yonkee and Lowe, in preparation). These springs may reflect relatively rapid upward ground-water flow parallel to the Wasatch fault zone in the fractured footwall, with impermeable gouge zones at depth limiting fluid flow across the fault zone (Yonkee and Lowe, in preparation).

Water Budget

Recharge to the Weber Delta subdistrict aquifer system includes: channel seepage from losing stretches of streams; seepage from irrigation ditches, irrigated fields, lawns, and gardens; direct infiltration of precipitation; and subsurface inflow from bedrock of the Wasatch Range (table 2). Most recharge takes place in the primary recharge area along the mountain front, especially near the mouth of Weber Canyon (Anderson and others, 1994). A large flood in 1952 may have significantly raised short-term ground-water levels in the Weber Delta subdistrict aquifer system. Subsurface inflow from bedrock along the mountain front and seepage from the Weber River are probably the dominant recharge sources.

Discharge from the Weber Delta subdistrict aquifer system includes: flow to gaining stretches of streams and to small springs; water-well withdrawal; evapotranspiration from shallow ground water; and ground-water flow to Great Salt Lake (table 2). Water-well withdrawal and flow to gaining streams and springs are the main discharge components (Clark and others, 1990).

Ground-water flow in the Weber Delta subdistrict aquifer system is generally westward from recharge areas near the Wasatch Range toward Great Salt Lake (Feth and others, 1966). The horizontal hydraulic gradient for deeper wells in the Delta aquifer is about 5 feet per mile (1 m/km) in most areas, and the horizontal hydraulic gradient for shallow wells in the Sunset aquifer is about 10 feet per mile (2 m/km) in most areas (Feth and others, 1966). The vertical hydraulic gradient in the system is generally downward in recharge areas near the mountain front, and generally upward where confined conditions are prevalent west of the mountain front, but vertical flow is probably relatively slow through low-permeability confining beds west of the mountain front (Clark and others, 1990).

Transmissivity values for confined parts of the Weber Delta subdistrict aquifer system range from 15,000 to 40,000 feet squared per day (1,400-3,700 m^2/d), based on four aquifer tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Transmissivity values for unconfined conditions near the mountain front in the Weber Delta subdistrict range from 4,000 to 5,300 feet squared per day (370-500 m^2/d), based on two aquifer tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Elastic storage coefficients for the aquifer system in the Weber delta subdistrict range from about 0.002 to 0.00007, based on tests conducted between 1944 and 1956 (Feth and others, 1966, table 8). Specific yields, related to dewatering of pore space, are likely in the range of 0.25 to 0.07, based on observed porosities and limited recharge tests (Feth and others, 1966).

Table 2. Hydrologic budgets for the Weber Delta District.

Recharge type	Feth and others (1966)[a] (km^3/yr)	Feth and others (1966)[a] (acre-feet/yr)	Gates (1995)[b] (km^3/yr)	Gates (1995)[b] (acre-feet/yr)	Clark and others (1990)[c] (km^3/yr)	Clark and others (1990)[c] (acre-feet/yr)
Channel seepage [d]	~ 0.025 [f]	~21,000 [f]	0.052	43,000	No separate estimate	
Other seepage [e]	0.007	6,000	0.007	6,000	No separate estimate	
Direct infiltration	0.012	10,000	0.008	7,000	No separate estimate	
Subsurface inflow	0.036	30,000	0.064	53,000	No separate estimate	
TOTAL	~ 0.084	~70,000	0.131	109,000	0.130	107,000
Discharge type						
Flow to streams, springs	~ 0.023[g]	~19,000[g]	0.070	58,000	0.045	38,000
Water-well withdrawal	0.030	25,000	0.030	25,000	0.060	50,000
Evapotranspiration	0.007	6,000	0.008	7,000	0.007	6,000
Flow to Great Salt Lake	0.025	20,000	0.023	19,000	0.018	15,000
TOTAL	~0.084	~70,000	0.131	109,000	0.131	109,000

[a] representative of time period 1953-1956 with well withdrawal for 1954; probably represents non-steady state conditions
[b] representative of time period 1953-1956, with values adjusted to approximate steady state conditions based on estimates of overall hydrologic budget for time period 1969-1984
[c] representative of time period 1969-1984, based on modeling study with values adjusted for water removal from storage
[d] includes losing stretches of stream channels and seepage from canals
[e] includes irrigated fields, lawns, and gardens
[f] approximate value, varies substantially between years
[g] adjusted to maintain water balance with total discharge = total recharge

The amount of potentially available ground water in the entire Weber Delta district was estimated by Clark and others (1990) to be about 37 million acre-feet (45 km^3), based on an average specific yield of 0.11 for fine- and coarse-grained materials with a total thickness of 1,500 feet (450 m), which is the entire thickness of Quaternary basin fill. Feth and others (1966) estimated the total amount of potentially available water from the Sunset and Delta aquifers in the central part of the district to be about 3 million acre-feet (4 km^3), based on a specific yield of 0.07 and a combined thickness of 400 feet (120 m) for coarse-grained intervals observed in wells; about 100,000 acre-feet (0.1 km^3) of this total was estimated to be available before dewatering of these principal aquifers would begin.

Seasonal water levels in the Weber Delta district generally rise in the spring during net recharge and decline in the summer, with the magnitude of water-level declines greatest near the mountain front (Clark and others, 1990). Long-term water levels in the aquifer system have declined slightly overall, probably related to increased withdrawals from wells for municipal and industrial use (figure 2; Clark and others, 1990). From 1953 to 1985, water levels declined an average of 27 feet (8 m) for wells located in the confined part of the aquifer system, including a maximum drop of 50 feet (15 m) near the principal pumping center for the aquifer system (Clark and others, 1990). From 1953 to 1985, water levels in the unconfined part of the aquifer system declined as much as 40 feet (12 m) in wells at the mouth of Weber Canyon (Clark and others, 1990), indicating that ground-water mining is occurring. Burden and others (2000) documented water-level declines of up to 30.8 feet (9.4 m) in the Weber Delta district from 1970 to 2000.

Water Quality

Ground-water quality in the Weber Delta subdistrict is generally high. Ground water in the subdistrict includes calcium-magnesium-bicarbonate, sodium-chloride, and mixed types (Smith and Gates, 1963; Feth and others, 1966; Bolke and Waddell, 1972; Clark and others, 1990). The calcium-magnesium-bicarbonate type occurs south of central Ogden City and includes the WRBASR project study area, and generally contains less than 300 milligrams/liter (ppm) total dissolved solids (TDS) (Feth and others, 1966, figure 14). Mixed type waters occur between the Ogden River and central Ogden City, and contain from 500 to 1,000 ppm TDS (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). The sodium-chloride type is generally known to occur north of the Ogden River, and contains from 500 ppm TDS at the mouth of Ogden Canyon to more than 2,000 ppm TDS in the northwestern part of Ogden City (Smith and Gates, 1963, figure 8; Feth and others, 1966, figure 14). However, Clark and others (1990, figure 44) extended the area where chloride concentrations exceed 250 ppm to include the entire area north of Burch Creek.

Concentrations of organic solvents, such as toluene and trichloroethane, that exceed ground-water-quality standards (appendix C) (U.S. EPA, 2002) have been identified on Hill Air Force Base, southeast of the WRBASR project study area, and are currently being remediated (Dalpias and others, 1989). The contamination is only in the upper aquifer system; ground water from the Delta aquifer currently meets all EPA ground-water standards.

Ground-water-quality data from Smith (1961, table 3), Smith and Gates (1963, table 4), Feth and others (1966, table 9), Bolke and Waddell (1972, table 2), Plantz and others (1986, table 5), and Clark and others (1990, table 13) do not indicate that tested wells in the WRBASR project study area have exceeded U.S. EPA (2002) ground-water-quality standards. However, wells in sections 30 and 29, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, directly east of the WRBASR project study area have moderately high nitrate concentrations, including respective maximum values of 7.4 and 5.0 ppm (Bolke and Waddell, 1972, table 2).

Public Water Supplies

Hill Air Force Base uses five wells in sections 29 and 30, T. 5 N., R. 1 W., Salt Lake Base Line and Meridian, immediately to the west of the WRBASR project study area for military and culinary purposes (Smith, 1961, table 1; Bolke and Waddell, 1972, table 1). The cities of South Weber, Riverdale, Washington Terrace, and South Ogden obtain some of their culinary water supplies from wells respectively located in sections 20 and 33, section 18, section 17, and section 8, all of T. 5 N., R. 1 W., Salt Lake Base line and Meridian (Bolke and Waddell, 1972, table 1). The town of Uintah obtains some of its water supply from a spring, and the Uintah Highlands area obtains some of its water supply from springs and wells, all likely located within the Weber Delta subdistrict (Utah Division of Water Resources, 1997, table 11-1); all of these communities may benefit directly from the WRBASR project. These wells are screened at least in part in the Delta aquifer.

DATA COLLECTION NEEDS

The WRBASR project consists of pre-recharge-experiment data collection for a period of approximately one year, recharge via either surface spreading (preferred) or well injection during spring runoff (most likely during April, May, and June, 2004), and post-recharge-experiment data collection for a period of approximately one year. The following types tasks need to be completed as part of the data-collection effort: (1) water levels in wells, (2) water-quality samples from wells, (3) water-quality samples from the Weber River, (4) microgravity and Global Positioning System surveys, (5) specific-capacity and aquifer tests from wells in the project study area, (6) construction of geologic cross sections, (7) construction and implementation of a ground-water flow model, (8) volume of surface water recharged to ground water during the artificial ground-water storage and recovery experiment, and (9) volume of artificially recharged ground water withdrawn.

Water Levels In Wells

Water levels in wells will be measured using electronic water-level indicators monthly for eleven months prior to the recharge experiment. Water levels will be measured daily for two weeks prior to the experiment, throughout the experiment, and until two weeks after the experiment has ended. Water levels will be measured monthly for the next 11 months after the experiment.

Water-Quality Samples From Wells

Water samples from wells will be collected and analyzed quarterly from one year prior to the experiment until one year after the experiment has ended, for the following constituents: NO_3+NO_2, TDS, Ca, Na, bicarbonate, CO_2, CO_3, Cl, Fe, K, SO_4, Mg, temperature, pH, Cu, and Pb. Results will be compared to EPA and State of Utah water-quality standards (appendix C).

Additionally, water samples from either a monitoring well drilled at the site of the recharge experiment (preferred) or the nearest downgradient water well will be collected and analyzed daily during the artificial recharge experiment. The latter data will help to estimate infiltration rates and evaluate geochemical changes in the newly recharged ground water as it travels downward through the aquifer.

Water-Quality Samples From The Weber River

At the site where water will be diverted from the Weber River as part of the artificial recharge experiment, water samples from the Weber River will be collected and analyzed quarterly from one year prior to the experiment until one year after the experiment has ended, for the following constituents: NO_3+NO_2, TDS, Ca, Na, bicarbonate, CO_2, CO_3, Cl, Fe, K, SO_4, Mg, temperature, pH, Cu, and Pb. Additionally, water samples from the Weber River will be collected and analyzed daily during the artificial recharge experiment.

Microgravity And Global Positioning System Surveys

A precision gravimeter can detect changes in mass below the earth's surface due to changes in storage and ground-water levels in aquifers, in both infiltration-basin and injection-well settings (Pool and Schmidt, 1997; Metzger and others, 2002). The precision gravity data can be used to detect mass changes associated with water-level changes of 5 feet (2 m) or more at depths of around 300 feet (100 m) when coordinated with precise control of land-surface elevation changes using Global Positioning System (GPS) surveys (Metzger and others, 2002). Gravity and GPS surveys must be conducted before, during, and after recharge phases to achieve these goals.

For the WRBASR project, a graduate student from the University of Utah will conduct the microgravity and GPS surveys and data reduction. The project will require establishing approximately 15 to 20 stations covering one square mile centered on the recharge basin or injection well. After the survey stations have been established, measurements will be made quarterly preceding the recharge experiment, to identify natural seasonal changes in ground-water storage and land-surface elevation. Measurements will also be made immediately before, during, and after the recharge experiment, and quarterly thereafter until the next recharge phase. The data will be used to estimate the volume, distribution, and movement of ground water introduced into storage below the infiltration pond or injection well.

Specific Capacity And Aquifer Test Data From Wells In The Project Study Area

Specific-capacity and aquifer-test data available from existing wells in the project study area have been collected and will be tabulated to determine hydrologic properties of the basin-fill aquifer to be used in construction of the ground-water flow model. Should any new wells be drilled, aquifer tests will be conducted on them to further improve our understanding of the hydrologic properties of the aquifer used for artificial ground-water storage and recovery.

Construction Of Geologic Cross Sections

Clyde and others (1984) constructed geologic cross sections through the WRBASR project study area (one example is shown in figure 5). All available data, including logs of water wells, will be collected and evaluated along the cross sections of Clyde and others (1984); these previous cross sections will be revised and new sections will be drawn, if necessary, to reflect current knowledge of the basin-fill aquifer and will be used to aid in construction of the ground-water flow model.

Construction And Implementation Of Ground-Water Flow Model

The application of computer-assisted simulation modeling of proposed recharge operations is recommended when the data available from literature and collected in the initial stages of the design are sufficient to justify hydrogeologic modeling (Pyne, 1995). The main goal for hydrogeologic modeling is to provide an improved basis for conceptual design of facilities and planning of the test program. Hydrogeologic modeling conducted after all geologic data have been collected, is an essential tool for planning and budgeting the project. Additionally, geochemical simulation might be considered whenever water quality of the recharging water raises environmental concerns. Geochemical modeling is also useful to evaluate mixing between recharged and native water in the presence of aquifer minerals. At the present stage of this study, a hydrogeologic model is considered to be of a significant importance.

A modular three-dimensional finite difference groundwater flow model (MOFLOW) is proposed to simulate artificial recharge in the study area (McDonald and Harbaugh, 1984, 1988). A MODFLOW model requires knowledge of the 3D spatial and hydrogeologic characteristics of all geologic layers, including porosity, hydraulic conductivity, specific yield, and storativity. Geologic data are used to support selection of boundary conditions for the model.

The Recharge Package (RCH) in MODFLOW is designed to simulate areally distributed recharge to the ground-water system. Areal recharge occurs, for example, as a result of precipitation that percolates to the ground-water system. The recharge is applied to a single cell within the vertical column of cells. There is no need to allow for recharge to occur simultaneously at multiple depths in the same vertical column because natural or artificial recharge enters the ground-water system at its top. The Recharge Package is recommended to simulate artificial recharge. The Recharge Package requires knowledge of the amount of recharge available during a specified period of time.

If the capability to apply recharge to more than one cell in a vertical column of cells is required, then the Well Package, which allows recharge or discharge to be specified at any model cell, can be used. The Well Package can simulate both recharge and discharge, so it can be used to model ASR. The Well package requires knowledge of the exact location of wells to be used in the artificial recharge operations, their diameter, the exact screened interval, and the amount of recharge or discharge for ASR systems.

Simulation of the effects of flow between surface water features and ground water will be conducted using the River Package. The River Package requires knowledge of river stage elevations, river bottom elevations, and river material conductance.

The results of modeling will be calibrated using all available geologic and hydrogeologic data. They will also be compared to results of modeling conducted for the area of study in 1983, prior to the development of MODFLOW (Hansen, 1983).

Volume Of Surface Water Recharged To Ground Water

The volume of surface water recharged to ground water will need to be measured during the experiment. The volume of surface water used in the experiment will not exceed available water rights.

Volume Of Artificially Recharged Ground Water Withdrawn

The volume of artificially recharged ground water that is withdrawn after the initial recharge experiment and subsequent implementation of the project will be difficult to estimate unless a well is installed within the recharge area and mixing with ground water already present in the aquifer is limited. If owners of existing wells downgradient of the recharge area obtain new water rights to withdraw additional water, it will not be possible to determine the proportion of water withdrawn that was introduced into the aquifer by artificial recharge.

SUMMARY

This report summarizes phase I of the WRBASR project, presenting the results of a literatures search and outlining data-collection needs for the project. During phase II, data will be collected, likely accompanied by a basic-data release. At the end of this project, a final report will likely be released, incorporating and superceding the material included in this report and the basic-data release.

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APPENDICES

APPENDIX A

DESCRIPTION OF MAP UNITS SHOWN ON FIGURE 3

Quaternary

Quaternary map units are surficial deposits grouped based on dominant depositional processes and their relationship to Bonneville lake-cycle stages (figure A.1, table A.1). Depositional process designators include: lacustrine (l), deltaic (d), alluvial (a), mass-wasting (m), and glacial (g). Relative-age designators include: pre-Bonneville (5), Lake Bonneville transgressive (4), Lake Bonneville regressive (3), older to middle Holocene (2), and younger Holocene (1). The descriptions of these map units are modified from Yonkee and Lowe (in review).

Lacustrine gravel-bearing deposits, Bonneville-transgressive (Qlg_4). This unit consists of moderately to well-sorted, medium- to thick-bedded, pebble- to cobble-clast gravel layers with minor to moderate amounts of sandy matrix interbedded with varying amounts of finer-grained

Table A.1 *Age (radiocarbon years B.P.) and elevation estimates for the principal shorelines of the Bonneville lake cycle (after Currey, D.R., unpublished data, and Oviatt and others, 1990, 1992; Oviatt, 1997).*

Shoreline	Phase	Elevation (ft)[1]	Age Estimate (10^3 years ago)
Stansbury	Transgressive	4,419 – 4,521	between 21 and 20
Bonneville	Transgressive	5,092 – 5,335	~15 - 14.5
Provo	Regressive	4,738 – 4,931	~14.5 – 14
Gilbert	Regressive	4,242 – 4,301	~10.9 - 10.3

[1] Shoreline elevations are reported as ranges because the amount of post-Lake Bonneville isostatic rebound is geographically variable.

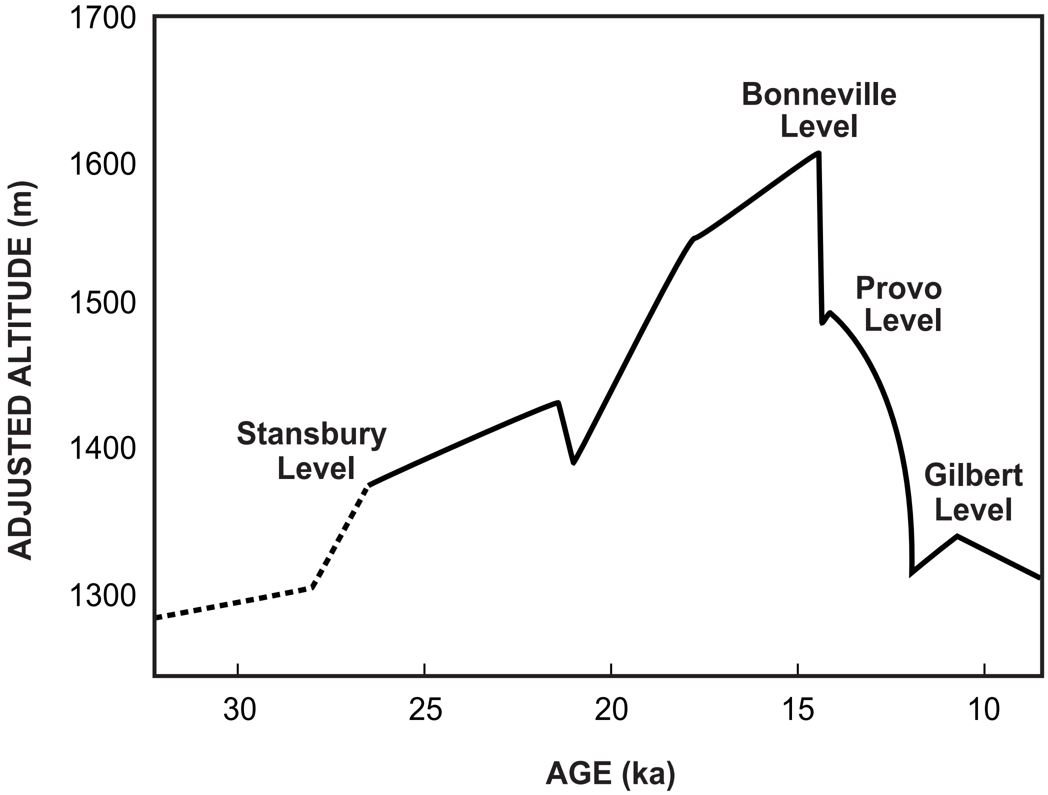


Figure A.1. *Hydrograph of Lake Bonneville and Great Salt Lake, 32,000- ~10,000 years ago (modified by Harty and Lowe, 2003; from Oviatt and others, 1992; Oviatt, 1997).*

intervals that increase in abundance away from the mountain front. Gravel clasts are mostly subrounded to rounded, but subangular clasts occur locally where alluvial-fan and landslide deposits were reworked along shorelines. Gravel-rich layers are best developed along the Bonneville shoreline (elevation 5,210 feet [1,590 m]). Finer grained intervals consist of thin-bedded silt, sand, and gravelly sand. This unit is exposed along the mountain front at elevations between the Provo and Bonneville shorelines, and grades westward into fine-grained lacustrine deposits (Qlf_4) that lack gravel layers. This unit is locally greater than 200 feet (60 m) thick along the mountain front north of the mouth of Weber Canyon.

Lacustrine fine-grained deposits, Bonneville transgressive (Qlf_4). This unit consists of varying amounts of sand, silt, and clay, and includes both very fine-grained intervals deposited in quiet, deep waters, and intervals deposited as delta bottomset beds. The very fine-grained intervals are most abundant farther away from Weber Canyon and the mountain front, whereas bottomset deposits are more abundant near the mouth of Weber Canyon. The unit is well exposed within a series of 200-foot-(60 m) high, 0.6-mile- (1 km) long ridges above the Provo shoreline (elevation 4,800 feet [1,460 m]) near the mouth of Weber Canyon. This unit may be up to 500 feet (150 m) thick near the mouth of Weber Canyon, including up to 300 feet (90 m) of deposits preserved in the subsurface; thickness appears to decrease to the north and west.

Delta deposits, Bonneville-transgressive (Qd_4). This unit consists mostly of clast-supported, subrounded to rounded, pebble and cobble gravel and gravelly sand deposited as topset beds. The gravel is moderately to well sorted, medium to thick bedded, and exhibits weak pebble imbrication and contains local channels. These deposits cap small hilly areas at an elevation of about 5,000 feet (1,520 m) northwest of the mouth of Weber Canyon. The thickness of exposed topset beds in this unit is about 7 to 13 feet (2-4 m).

Delta deposits, Bonneville-regressive (Qd_3). This unit consists mainly of sandy foreset and gravelly topset beds that form a large, gently west-sloping, composite delta deposited by the Weber and Ogden Rivers. The foreset deposits consist of interlayered beds of fine to medium, moderately to well-sorted sand, silt, and clay. The topset deposits consist mostly of clast-supported, subrounded to rounded, pebble and cobble gravel, with some gravelly sand; the gravel is moderately to well sorted, medium to thick bedded, and displays weak pebble imbrication and local channels. The topset gravels are up to 20 feet (6 m) thick. The foreset deposits are greater than 30 feet (9 m) thick in western parts of the Weber River delta, but are absent near the mouth of Weber Canyon east of the Provo shoreline (elevation 4,800 feet [1,460 m]) where the delta was incised into older lacustrine deposits.

The unit also includes gravels deposited as the Weber River incised into older deposits, forming multiple terraces between 100 and 300 feet (30 and 90 m) above the modern Weber River. These terraces are graded to various lower delta levels and regressive shorelines partly exposed to the west of the study area. The subrounded to rounded, pebble to cobble sized gravel is moderately to well sorted with some sandy matrix, medium to thick bedded, and displays pebble imbrication and local channels. Where exposed, the terrace gravels are up to 20 feet (6 m) thick.

Alluvial terrace deposits, older Holocene (Qat_2). This unit consists mainly of clast-supported, pebble to cobble gravel and minor gravelly sand forming terraces found about 30 to 50 feet (9-15

m) above the modern Weber River. The terraces were deposited when the Weber River was graded to base levels below the Gilbert shoreline (elevation 4,240-4,245 feet [1,292-1,294 m] in the Roy quadrangle; Sack, 2003). The gravel is moderately to well sorted, medium to thick bedded, contains subangular to rounded clasts, and displays pebble imbrication and local channels. Where exposed, this unit is less than 6 meters (20 ft) thick.

Stream alluvium, undivided (Qal). These deposits consist mainly of gravel, gravelly sand, and finer grained overbank deposits along active stream channels and in inactive, low-level benches. The gravel is clast-supported, mostly pebble to cobble sized, moderately to well sorted with some silty to sandy matrix, medium to thick bedded, and displays clast imbrication and channels. Clasts range from subangular to rounded, and are derived from mixed Paleozoic to Mesozoic sedimentary rock and Precambrian basement rock exposed in the Weber River drainage basin. Thin-bedded sand to silt comprise the overbank deposits. The undivided unit is mapped along the Weber River in Weber Canyon where separate alluvial deposits are too narrow to map separately. The deposits include minor matrix-supported debris-flow deposits along mountain stream channels, and are up to 40 feet (12 m) thick.

Stream alluvium, middle Holocene (Qal_2). This unit consists mostly of gravel and minor gravelly to silty sand forming benches about 10 to 30 feet (3-9 m) above the Weber River's active flood plain. The mostly pebble- to cobble-sized gravel is clast supported, moderately to well sorted with some silty to sandy matrix, medium to thick bedded, and displays clast imbrication and channels. Clasts range from subangular to rounded, and have mixed Paleozoic to Mesozoic sedimentary rock and Precambrian basement rock compositions, reflecting the wide variety of rock types in the Weber River drainage basin. Where exposed, the unit is less than 20 feet (6 m) thick.

Stream alluvium, younger Holocene (Qal_1). This unit consists mostly of gravel and some finer grained overbank deposits along modern channels and recently active flood plains of the Weber River. The gravels have characteristics similar to those described for middle Holocene stream alluvium. The overbank deposits consist of thin-bedded sand and silt. This unit is estimated to be about 10 to 20 feet (3-6 m) thick.

Alluvial-fan deposits, undivided (Qaf). This undivided unit consists of complexly interlayered alluvial gravels and debris-flow deposits forming fan-shaped landforms. The alluvial gravels are typically clast supported, thin to thick bedded, moderately sorted, and contain angular to rounded, pebble to cobble clasts with variable amounts of sandy to silty matrix. The debris-flow deposits are typically matrix supported, unstratified, poorly to non-sorted, and contain angular to subangular, pebble to boulder clasts; boulders can be up to 6 feet (2 m) in diameter. The undivided unit is mapped where relative age cannot be assigned based on morphologic and crosscutting relations of the fans. These fan deposits, where exposed, are less than 30 feet (9 m) thick.

Alluvial-fan deposits, Bonneville-transgressive (Qaf_4). These deposits comprise fan-shaped landforms having upper surfaces that are graded to the Bonneville shoreline, and that generally display subdued morphology and are deeply incised by modern streams. The deposits consist of complexly interlayered alluvial gravels and debris-flow deposits, like those described for undivided alluvial fans, but locally display increased rounding of clasts and decreasing amounts of fine-grained matrix near the Bonneville shoreline. These fan deposits grade locally into gravel-bearing lacustrine deposits (Qlg_4). These fans may be locally greater than 200 feet (60 m) thick, but fan thickness is difficult to determine.

Alluvial-fan deposits, Bonneville-regressive (Qaf_3). These deposits comprise fan-shaped landforms that are graded to the Provo or other recessional shorelines, and that generally display subdued channels and levees; these alluvial fans are locally incised into transgressive alluvial fans (Qaf_4), but are incised by modern streams. Regressive fans also consist of complexly interlayered alluvial gravels and debris-flow deposits, like those described for undivided alluvial fans, but the gravels contain more rounded clasts derived from reworking of older lacustrine gravels. These fans generally have exposed thicknesses of less than 30 feet (9 m).

Alluvial-fan deposits, middle and older Holocene (Qaf_2). These deposits comprise fan-shaped landforms that are slightly incised by modern streams, have moderately fresh channels and levees, and, where the deposits are crossed by the Wasatch fault zone, exhibit 10- to 30-foot- (3-9 m) high fault scarps. Like other alluvial fans, these deposits consist of complexly interlayered alluvial gravels and debris-flow deposits. The alluvial gravels are a mixture of angular to subrounded stream clasts and reworked, rounded lacustrine clasts, with variable amounts of sandy to silty matrix. The debris-flow deposits contain mostly angular clasts with abundant fine-grained matrix. These alluvial fans generally have exposed thicknesses of less than 20 feet (6 m).

Alluvial-fan deposits, younger Holocene (Qaf_1). These deposits comprise fan-shaped landforms that are graded to modern stream or local base levels, have relatively well-defined channels and levees, and, where the deposits are crossed by the Wasatch fault zone, exhibit fault scarps that are less than 10 feet (3 m) high. These alluvial fans also consist of interlayered gravel and debris-flow deposits. The alluvial gravels are a mixture of angular to subrounded and reworked, rounded clasts. The debris-flow deposits contain mostly angular clasts with an abundant fine-grained matrix. The larger boulder clasts are up to 6 feet (2 m) in diameter. These alluvial fans are probably less than 20 feet (6 m) thick.

Landslide deposits, undivided (Qms). This undivided unit consists of unsorted, unstratified, clay- to boulder-rich diamicton and displaced bedrock blocks. Clasts in the deposits are generally angular and have compositions that reflect local source materials. This undivided unit is mapped above the Bonneville shoreline where age relations are uncertain. These deposits display distinct hummocky topography and local seeps, and are found mostly along steeper, north-facing slopes. Areas with indistinct hummocky topography that may be older landslides and hillslope colluvium are mapped as Qms?.

Landslide deposits, pre-Bonneville to Bonneville-transgressive (Qms_5). These deposits are locally cut and reworked along the Bonneville shoreline, and the toes of the landslides are locally covered by thin lacustrine deposits, indicating they moved before Lake Bonneville rose to its highest level. However, parts of some of these landslides were likely active during the Bonneville transgression, and parts of some of these landslides may have been reactivated more recently. These deposits consist of clay- to boulder-rich diamicton with very large bedrock blocks that have been variably translated and rotated. These landslides have subdued hummocky topography and head scarps, and are found along steeper slopes above and near the Bonneville shoreline. The thicknesses of the deposits are likely highly variable. Areas that have randomly oriented bedrock blocks but lack distinct hummocky topography are mapped as Qms_5?.

Landslide deposits, middle and older Holocene (Qms_2). This unit includes: (1) widespread slides that developed mostly within finer grained lacustrine and delta deposits along moderate slopes formed by downcutting of the Weber River, (2) slides in fine-grained lacustrine deposits along steep to moderate slopes below the Bonneville shoreline, and (3) slides along steeper slopes in the Wasatch Range that reactivated parts of older slides. Type 1 and 2 deposits consist mostly of sand, silt, and clay that have disrupted bedding and landslide-related faults (Feth and others, 1966). These deposits exhibit hummocky topography, have subdued to moderately fresh head scarps, and locally form amphitheater-shaped regions. Type 3 deposits consist of clay- to boulder-rich diamicton with large bedrock blocks that have more distinctly hummocky topography compared to the older slides that they reactivated.

Landslide deposits, younger Holocene (Qms_1). This unit includes landslides that have experienced recent movement and typically have fresh scarps, local ground cracks, and distinctly hummocky surfaces. This unit includes: (1) landslides that reactivated parts of older landslides within lacustrine and delta deposits, and (2) small landslides that reactivated parts of older landslides or formed in colluvium along steeper slopes in the Wasatch Range and along the mountain front. Type 1 landslides consist mostly of sand, silt, and clay, typically have highly disrupted bedding and local seeps, and tend to form in areas with abundant, near-surface water and overall moderate slopes (Pashley and Wiggins, 1972; Lowe and others, 1992). Type 2 landslides consist of clay- to boulder-rich diamicton, with clast and matrix compositions that reflect local source materials.

Debris-flow deposits (Qmf). These deposits typically consist of matrix- to clast-supported, cobble to boulder gravel with variable amounts of sandy to clayey matrix. The deposits are generally poorly to non-sorted, non-layered, and locally exhibit rock levees and central channels. These deposits are present in some mountain canyons, and may contain multiple flows of various ages, including flows graded to the Bonneville or Provo shorelines, Holocene flows that are incised into older flows, and historically active flows. However, because individual flows are small relative to map scale and correlating ages of flows between canyons is difficult, all debris-flow deposits are grouped into one map unit. Debris-flow deposits are generally less than 30 feet (9 m) thick.

Talus (Qmt). These deposits consist of angular, pebble- to boulder-sized rock debris with little or no matrix. The talus forms scree slopes with little or no vegetation at the bases of cliffs and steeper bedrock slopes. The talus blocks have compositions that reflect the nearby bedrock sources. Talus deposits grade into colluvium that has been partly stabilized by vegetation. The thickness of the deposits is uncertain, but is probably less than 50 feet (15 m) in most areas.

Colluvium (Qc). Colluvium consists of variably clayey to sandy, pebble to boulder gravel and diamicton, that have moved and been deposited mostly by slope wash and creep. These deposits also include small areas of debris and alluvial cones, talus, landslides, alluvium, avalanche deposits, and bedrock exposures. Colluvial deposits are matrix to rarely clast supported, generally poorly to non-sorted, weakly to non-stratified, and contain angular to subangular clasts with variable amounts of sandy to clayey matrix. This unit is mapped along slopes in the

Wasatch Range and some scarps of the Wasatch fault zone. The total thickness of colluvial deposits is probably less than 50 feet (15 m) in most areas.

Colluvium and alluvium, undivided (Qac). This unit includes hillslope colluvium and stream alluvium, with small areas of debris cones, landslides, and bedrock exposures. This unit consists of non-sorted, unstratified, clay- to boulder-rich diamicton, and moderately sorted, cobble gravel to sand with subangular to subrounded clasts deposited along channels and slopes near some ephemeral streams in the Wasatch Range. Modern channels are locally incised up to 20 feet (6 m) into these deposits, indicating a long history of accumulation and recent local erosion. These deposits are probably less than 50 feet (15 m) thick in most areas.

Artificial fill (Qf). This unit consists of debris that was excavated and reworked or imported into the area during construction of roads and railways along Weber Canyon. Smaller areas of fill and disturbed ground were not mapped.

Tertiary

Tertiary igneous dikes (Td). Two small igneous dikes (NE1/4 section 24 and N1/2 section 25, T. 5N., R. 1W.) crosscut rocks of the Farmington Canyon Complex. These dikes are non-foliated and are composed of hornblende, biotite, and plagioclase phenocrysts in a fine-grained, altered matrix.

Early Proterozoic Farmington Canyon Complex

Meta-ultramafic and mafic rocks (Xfu). This unit consists of pods of ultramafic rock, amphibolite, and minor hornblendite. The ultramafic rock is variably foliated and is composed of abundant pyroxene, amphibole, and minor olivine that are partly altered to serpentine and talc, and minor oxides. The amphibolite is well foliated and is composed of abundant hornblende and plagioclase, with some oxides, and rare pyroxene. Hornblendite is found locally along contacts between the ultramafic and amphibolite bands.

Quartz-rich gneiss (Xfq). This unit consists mostly of layers of quartz-rich gneiss composed dominantly of quartz, with lesser amounts of plagioclase, biotite, and mica. Locally, the plagioclase is partly altered to sericite, and the biotite is partly altered to chlorite. Geochemically, quartz-rich gneiss contains very high contents of SiO_2 (tableA.2). Foliation in this unit is subparallel to the overall layering. This unit also includes some thin layers of biotite-rich schist and amphibolite.

Biotite-rich schist (Xfb). This unit consists mostly of layers of biotite-rich schist containing widespread sillimanite and garnet. The schist layers contain greater than 20 volume percent (vol%) biotite, with variable amounts of sillimanite, garnet, quartz, plagioclase, K-feldspar, and minor oxides. Locally, the biotite and garnet are partly altered to chlorite, and the plagioclase is partly altered to sericite and epidote. The whole-rock chemical composition of the biotite-rich schist is relatively rich in Al_2O_3 and poor in SiO_2 (table A.2). The unit exhibits a strong foliation that is partly defined by a preferred orientation of biotite, and local compositional layering is defined by alternating darker, biotite-sillimanite-rich bands and lighter, quartz-feldspar-rich bands. The schist is cut by widespread pegmatite pods, which consist of abundant quartz and feldspar, minor biotite, and garnet grains. This unit also contains some thin layers of amphibolite, quartz-rich gneiss, and granitic gneiss, and grades into migmatitic gneiss with decreasing biotite content.

Table A.2. Average whole-rock chemistry of Farmington Canyon Complex rock types (from Yonkee and Lowe, in review).

	quartz-rich gneiss[(a)]	biotite-rich schist[(b)]	amphi-bolite[(c)]	migmatitic gneiss[(d)]	granitic gneiss[(e)]	phyllonite, mylonite[(f)]	cata-clasite[(g)]
wt%							
SiO_2	92.4	54.4	48.5	71.1	69.6	70.7	68.9
Al_2O_3	3.8	20.1	14.4	12.5	12.0	12.3	11.9
FeO	0.4	9.4	11.1	6.1	6.5	5.8	6.2
MgO	0.1	3.8	7.6	0.5	0.4	3.8	2.3
CaO	0.1	1.4	10.2	1.7	2.0	0.4	0.5
Na_2O	0.5	1.6	2.4	2.8	2.8	0.6	2.5
K_2O	1.3	3.4	1.2	3.9	4.3	2.6	4.0
TiO_2	0.1	1.1	1.0	0.5	0.6	0.5	0.5
P_2O_5	0.0	0.2	0.1	0.1	0.2	0.1	0.1
LOI	0.5	3.5	1.0	0.7	0.6	3.4	2.8

(a) average of two samples reported by Bryant (1984; table 2) and one sample from this study
(b) average of two samples reported by Bryant (1984; table 2)
(c) average of four samples reported by Bryant (1984; table 3), includes amphibolite dikes within migmatitic gneiss and meta-gabbro in granitic gneiss
(d) average of ten samples from along Weber Canyon (Yonkee and Lowe, in review)
(e) average of four samples reported by Bryant (1984; table 1) and six samples from Yonkee and Lowe (in review)
(f) average of eleven samples from shear zone in Weber Canyon (Yonkee and Lowe, in review)
(g) average of ten samples along trace of Ogden floor thrust (Yonkee and Lowe, in review)

Migmatitic gneiss (Xfm). This unit consists mostly of migmatitic, fine- to medium-grained, mostly garnet- and biotite-bearing, quartzo-feldspathic gneiss. The migmatitic gneiss contains about 20 to 40 vol% quartz, 20 to 40 vol% K-feldspar, 20 to 40 vol% plagioclase, 0 to 20 vol% garnet, 0 to 20 vol% biotite, and minor oxides; some samples also contain up to 5 vol% hornblende and rare orthopyroxene. Locally, the plagioclase is partly altered to sericite and epidote, the K-feldspar is slightly altered to sericite, and the biotite and garnet are partly altered to chlorite. The whole-rock chemical composition of the migmatitic gneiss is similar to the composition of granitic gneiss, but is more variable and typically has a slightly higher Al_2O_3 and SiO_2 content and a slightly lower K_2O content (table A.2). The unit exhibits a strong foliation defined by the preferred orientation of biotite and quartz aggregates. The gneiss is cut by widespread coarse-grained granitic to pegmatitic dikes composed mostly of coarse-grained feldspar and quartz, with rare orthopyroxene and minor garnet. This unit also contains widespread thin layers of amphibolite, bands of hornblende-bearing granitic gneiss, and local layers of biotite-rich schist. The unmapped amphibolite layers are widespread within this unit (and within the quartz-rich gneiss and biotite-rich schist units) and are composed mostly of hornblende and plagioclase with accessory oxides, although some layers also contain minor biotite and quartz. The amphibolite layers contain about 50 weight percent (wt%) SiO_2 (table A.2).

Granitic gneiss of Ogden hanging wall (Xfgh). This unit consists of medium- to fine-grained, hornblende-bearing, granitic gneiss, and is exposed in several east-trending belts north and south of Weber Canyon. The granitic gneiss is composed of about 20 to 35 vol% quartz, 20 to 35 vol% plagioclase, 25 to 35 vol% K-feldspar, 3 to 15 vol% hornblende, 0 to 5 vol% biotite, and monor oxides and orthopyroxene. The plagioclase is partly altered to sericite and epidote, the K-feldspar is slightly altered to sericite, and the hornblende is partly altered to chlorite and a light-blue, fine-grained amphibole in some areas. The granitic gneiss is strongly foliated and contains about 70 wt% SiO_2 and has relatively high FeO and K_2O contents (table A.2). The granitic gneiss is cut by coarse-grained granite and pegmatitic dikes. These dikes are composed mostly of feldspar and quartz, but some dikes also contain minor hornblende and orthopyroxene. This unit is locally interlayered with the migmatitic gneiss, and contains small pods of meta-gabbro and amphibolite.

Chloritic gneiss, cataclasite, and mylonite (Kc). This unit consists of protoliths of the Farmington Canyon Complex that have undergone variable degrees of greenschist facies alteration and deformation. The chloritic gneiss exhibits moderate to strong chlorite alteration, moderatly to closely spaced fractures, some micaceous cleavage and fault and shear zones, and, locally, quartz-filled veins. The cataclasite exhibits extensive alteration, abundant angular fragments in a fine-grained, highly comminuted matrix, and widespread quartz veins. The mylonite and mica-rich phyllonite exhibit extensive alteration, and strong foliation is exemplified by quartz ribbons and mica aggregates. The altered gneiss, cataclasite, mylonite, and phyllonite are geochemically depleted in alkalies, especially CaO, and enriched in MgO compared to the basement rocks they were formed from (table A.2).

APPENDIX B

WELL-NUMBERING SYSTEM

The numbering system for wells in this study is based on the Federal Government cadastral land-survey system that divides Utah into four quadrants (A-D) separated by the Salt Lake Base Line and Meridian (figure D.1). The study area is in the northwestern quadrant (B). The wells are numbered with this quadrant letter (B), followed by township and range, all enclosed in parentheses. The next set of characters indicates the section, quarter section, quarter-quarter section, and quarter-quarter-quarter section designated by letters a through d, indicating the northeastern, northwestern, southwestern, and southeastern quadrants, respectively. A number after the hyphen corresponds to an individual well within a quarter-quarter-quarter section. For example, the well (B-5-1)36bbb-1 would be the first well in the northwestern quarter of the northwestern quarter of the northwestern quarter of section 36, Township 5 North, Range 1 West (NW¼NW¼NW¼ section 36, T. 5 N., R. 1. W.).

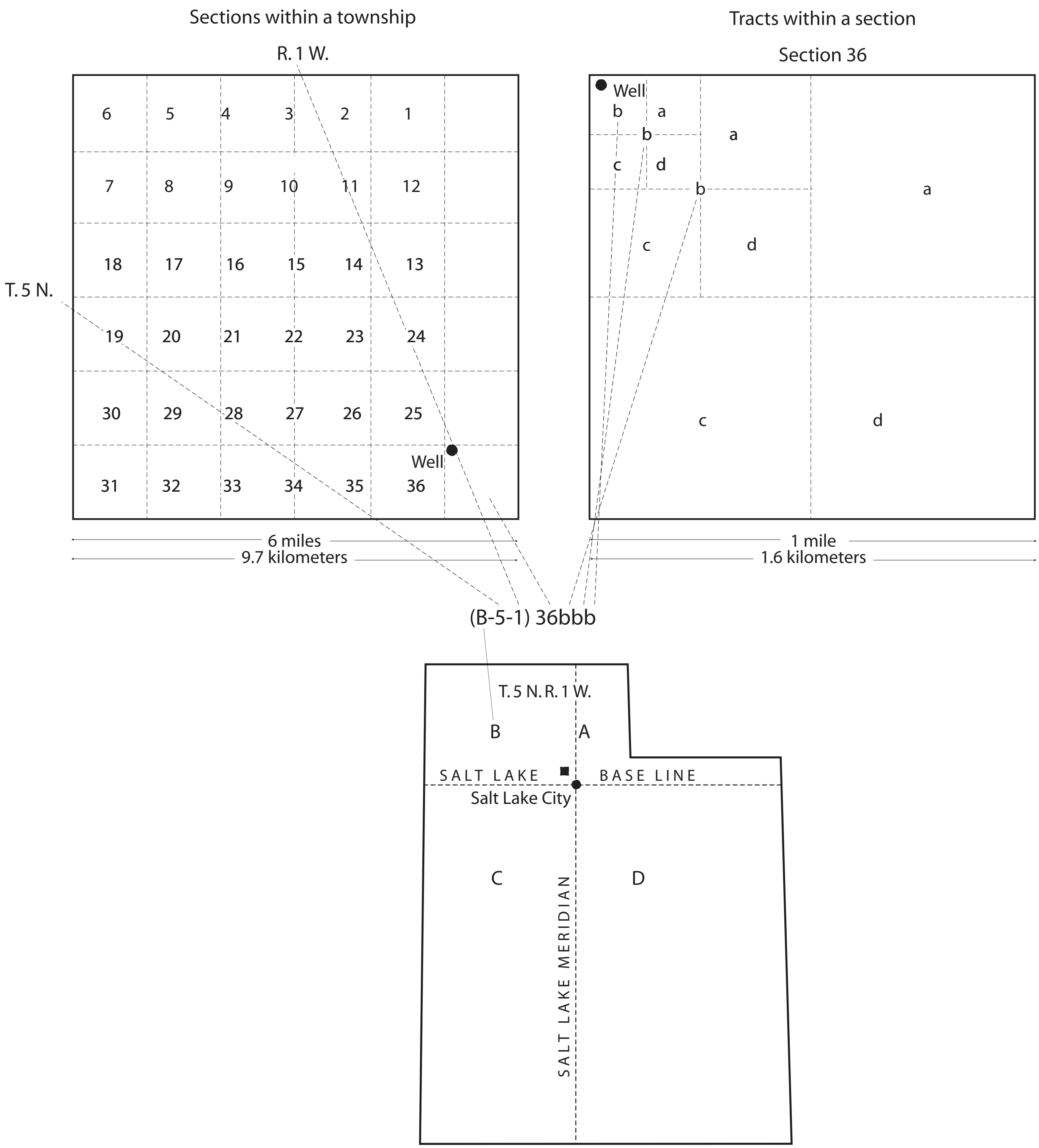
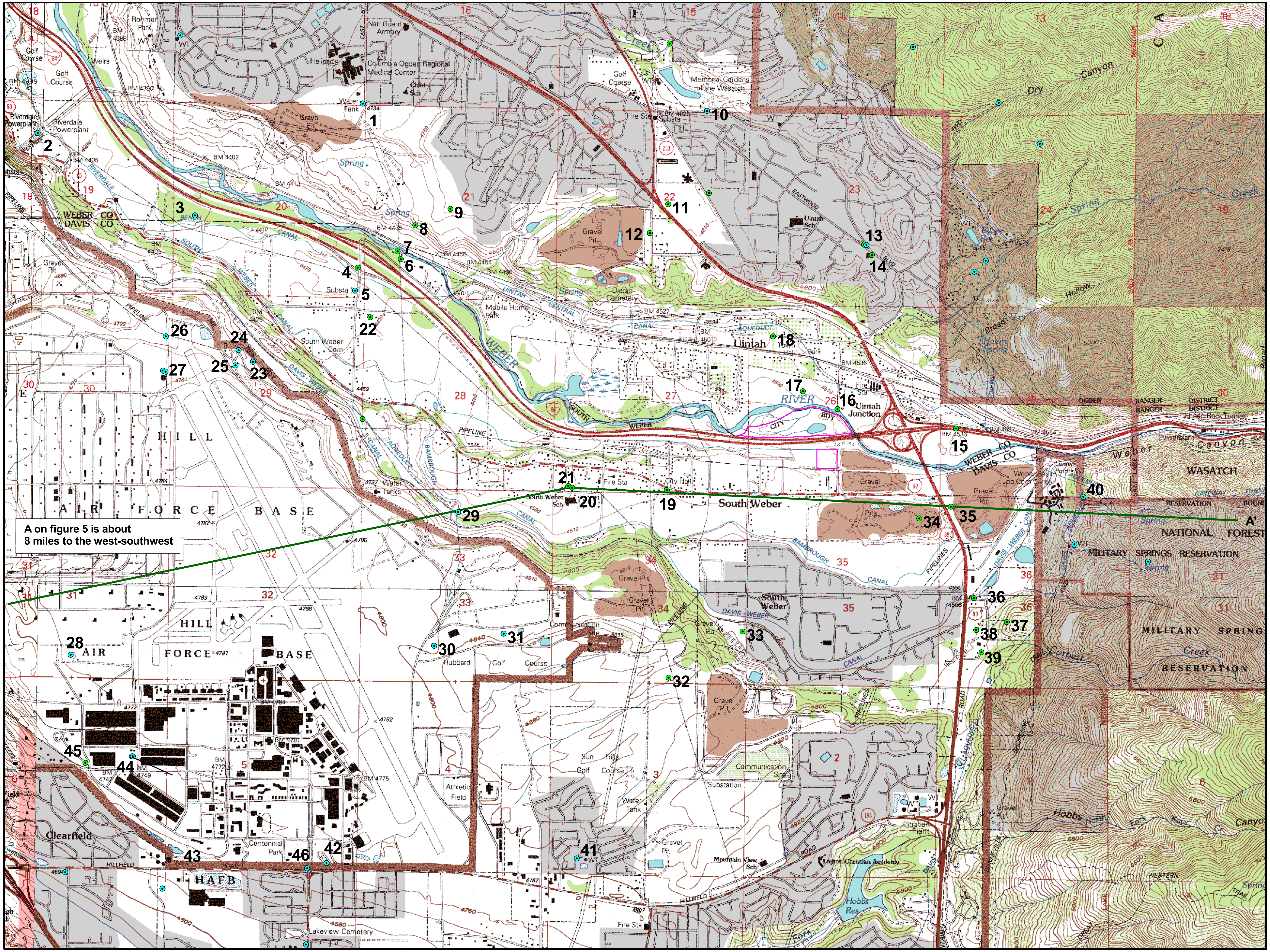


Figure B.1. *Numbering system for wells in Utah (see text for additional explanation).*

Table B.1 *List of wells shown on plate 1. ID number corresponds to number beside well on plot* and to circled number on log. Logs for some wells have not been located.

ID	OWNER	LOCATION	Log?
1	Washington Terrace	N 180 W 200 SE 5N 1W 17	Y
2	Weber Basin Water Conservancy District	S 1100 E 1100 NW 5N 1W 19	Y
3	Weber Basin Water Conservancy District	N 2150 W 50 SE 5N 1W 19	Y
4	US Bureau of Rec	N 740 W 165 SE 5N 1W 20	Y
5	Weber Basin Central	N 150 W 198 SE 5N 1W 20	Y
6	Nistler, Ronald	N 1100 E 950 SW 5N 1W 21	Y
7	Winchester, Brent	N 1195 E 805 SW 5N 1W 21	Y
8	Union Pacific RR	S 3310 E 1225 NW 5N 1W 21	Y
9	BYBEE, BRUCE E.	N 2400 W 100 S4 5N 1W 21	Y
10	Uintah Highlands Improvement District	section 22	N
11	Ryujin, George	N 2600 E 270 S4 5N 1W 22	Y
12	?	S 4293 W 146 N4 5N 1W 22	Y
13	Uintah Highlands Improvement District	N 1620 E 2020 SE 5N 1W 23	Y
14	Uintah Ward LDS church	N 1400 W 1903 SE 5N 1W 23	Y
15	Dansie	S 700 E 350 W4 5N 1W 25	Y
16	Bybee, Bruce E.	N 2344 W 168 S4 5N 1W 26	Y
17	CROFTS, DOUGLAS W.	N 250 E 1500 W4 5N 1W 26	Y
18	VALLEY NURSERY INC.	S 870 E 659 NW 5N 1W 26	Y
19	SOUTH WEBER TOWN	N 46 E 453 S4 5N 1W 27	N
20	US Bureau of Reclamation	N 61.05 E 456.83 SW 5N 1W 27	Y
21	US Bureau of Reclamation	N 67.05 E 456.83 SW 5N 1W 27	Y
22	SPAULDING, LLOYD	S 558 E 155 NW 5N 1W 28	Y
23	Hill Air Force Base	section 29	N
24	Hill Air Force Base	section 29	N
25	Hill Air Force Base	section 29	N
26	Hill Air Force Base	N 1475 W 139 E4 5N 1W 30	Y
27	Hill Air Force Base	N 500 W 208 E4 5N 1W 30	Y
28	Clearfield City	N 636 E 2492 SW 5N 1W 31	Y
29	Weber Basin Central	S 618 W 60 N4 5N 1W 33	Y
30	Hill Air Force Base	section 33	N
31	Hill Air Force Base	S 1632 W 3275 E4 5N 1W 33	Y
32	USA DEPARTMENT OF THE AIR FORCE	N 150 W 2150 SE 5N 1W 34	Y
33	WATERS, CALVIN T. AND GEORGIA C.	N 1450 W 550 SE 5N 1W 34	Y
34	CLARENCE WATERFALL COMPANY	S 634 W 558 NE 5N 1W 35	Y
35	US Bureau of Rec	S 73o10' E 214 NW 5N 1W 36	Y
36	Kenndedy, Leo	S 75 E1230.75 W4 5N 1W 36	Y
37	SMITH, RONALD J.	S 850 E 1880 W4 5N 1W 36	Y
38	O'NEILL, ROBERT M.	S 1075 E 1035 W4 5N 1W 36	Y
39	Charlesworth, Terry	N 910 E 1250 SW 5N 1W 36	Y
40	South Weber Water System	section 25 or 36	N
41	City of Layton	N 1100 E 920 SW 4N 1W 3	Y
42	Layton Water System	section 5	N
43	City of Clearfield	N 125 E 50 SW 4N 1W 5	Y
44	Hill Air Force Base	S 2122 W 938 NE 4N 1W 6	Y
45	Hill Air Force Base	S 2320 W 2320 NE 4N 1W 6	Y
46	Hill Air Force Base	section 5 or 8	N

Topographic Map and Locations of Water Wells, Weber River Basin Aquifer Storage and Recovery Project Study Area



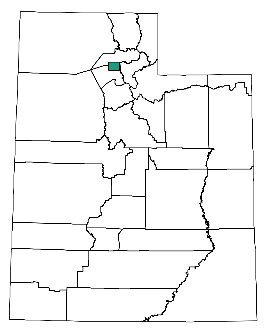
Explanation

Study-area boundary

Potential area for pilot project

14 Water well - label number corresponds to ID in table B.1

A——A' Cross section - see figure 5



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UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources